THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Impact on the Distribution System due to Plug-In Electric Vehicles and Changes in Electricity Usage

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To my family and friends

Abstract

Replacing conventional vehicles by Plug-in Electric Vehicles (PEVs) would likely increase electricity demand and put higher stress on the electrical power system. This thesis presents an approach to evaluate the impact on electrical distribution systems (DSs) caused by charging PEVs and load management of heating loads. The approach considers both vehicle usage statistics and demographic data to estimate when PEVs could be charged in different parts of a DS.

A case study was performed on a residential and a commercial part of the DS in Gothenburg. Three different control strategies for the charging were investigated, i.e. uncontrolled, loss-optimal and price-optimal strategies. The control strategies would have a significant effect on the timing of the charging, as well as the access of available infrastructure for charging.

The results showed that if all vehicles were PEVs and charged uncontrolled, peak demand would increase by between 21 - 35% in the residential area and by between 1-3% in the commercial area. If customers were directly exposed to the spot price at the Nordic day-ahead market and would charge according to the price-optimal control strategy, peak power would increase by 78% for the residential area and 14% for the commercial area. If the charging were controlled according to the loss-optimal control strategy, the charging would be conducted during off-peak hours without increasing peak demand, even if all vehicles were PEVs.

By controlling the heating loads in the residential area according to the price-optimal control strategy peak demand would increase by more than 80%, while peak demand would be reduced by almost 10% if the loss-optimal control strategy were applied.

Keywords: Electrical distribution system, Electric vehicle (EV), Load management, Open loop radial distribution system, Plug-in Electric Vehicle (PEV), Plug-in hybrid electric vehicle (PHEV)

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David Steen
Gothenburg,
Sweden, 2012

List of Publications

The publications originating from this project are:

[I] Lina Bertling, Ola Carlson, Sonja Lundmark and David Steen, "Integration of Plug-in Hybrid Electric Vehicles and Electric Vehicles - Experience From Sweden."
Power and Energy Society General Meeting, 2010 IEEE.

[II] Saman Babaei, David Steen, Tuan Le, Ola Carlson and Lina Bertling, "Effects of Plug-in Electric Vehicles on Distribution Systems: The Real Case of Gothenburg."
IEEE PES Conference on Innovative Smart Grid Technologies Europe, Gothenburg, Sweden, October 10-13, 2010.

[III] David Steen, Tuan Le, Miguel Ortega-Vazquez Ola Carlson, Lina Bertling and Viktoria Neimane, "Scheduling Charging of Electric Vehicles for Optimal Distribution Systems Planning and Operation."
CIRED, Frankfurt, Germany, June 6-9, 2011.

[IV] David Steen, Salem Al-Yami, Tuan Le, Ola Carlson and Lina Bertling, "Optimal Load Management of Electric Heating and PEV Loads in a Residential Distribution System in Sweden. "
IEEE PES Conference on Innovative Smart Grid Technologies Europe, Manchester, UK, December 5-7, 2011,

[V] David Steen, Tuan Le, Ola Carlson and Lina Bertling, "Assessment of Electric Vehicle Charging Scenarios Based on Demographical Data."
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Contents

List of Abbreviations

The following list presents abbreviations that are used throughout this thesis:

EPS	Electrical Power System
DSO	Distribution System Operator
DS	Electrical Distribution System
LV-DS	Low Voltage Distribution System
OLR-DS	Open Loop Radial Distribution System
DG	Distributed Generation
DES	Distributed Energy Storage
V2G	Vehicle To Grid
PHEV	Plug-in Hybrid Electric Vehicle
HEV	Hybrid Electric Vehicle
EV	Electric Vehicle
PEV	Plug-in Electric Vehicle
ZEV	Zero Emission Vehicle
DME	Dimethyl Ether
SS	Sectionalizing switches
TS	Tie switches

List of Nomenclatures

The following list presents nomenclatures that are used throughout this thesis:

$\mathbf{PEV}_{max}$	Maximum number of PEVs
$\mathbf{PEV}_{share}$	PEV penetration rate (1 = 100% PEVs)
$\mathbf{V}_h^W$	No. of vehicles stopping at work at hour h
$\mathbf{V}_h^H$	No. of vehicles stopping at home at hour h
$\mathbf{V}_h^{SL}$	No. of vehicles used for shopping and leisure journeys stopping at home at hour h
$\mathbf{V}_h^{H\ P}$	No. of vehicles parked at home at hour h
$\mathbf{V}_h^{W\ P}$	No. of vehicles parked at work at hour h
$\mathbf{V}_h^{SL\ P}$	No. of vehicles used for shopping and leisure journeys parked at home at hour h
$\mathbf{CP}_P$	Active charge power
$\cos\varphi$	Power factor of the charger
$\mathbf{CT}$	Charge time
$\boldsymbol{Dist}$	Average driving distance
$\boldsymbol{Cons}$	Average energy consumption [kWh/km]
η	Charge efficiency (*"Grid to Battery"*)
$\mathbf{P}_{i,h}^{PEV}$	Active PEV load at bus i at hour h
$\mathbf{Q}_{i,h}^{PEV}$	Reactive PEV load at bus i at hour h

$\mathbf{P}_{i,h}$	Power at bus i at hour h
$\mathbf{P}_{i,h}^{base}$	Forecast non-variable power demand at bus i at hour h
$\mathbf{P}_{i,h}^{var}$	Forecast variable power demand at bus i at hour h
$\mathbf{P}_{D_{i,h}}$	Forecast power demand at bus i at hour h
$\mathbf{P}_{loss}$	Losses in the DS
$\boldsymbol{i}$	Bus index
$\boldsymbol{h}$	Hour index
$\boldsymbol{n}$	No. of buses
$\mathbf{G}_{i,j}$	Conductance of cable (i,j)
$\mathbf{Y}_{i,j}$	Element of the network admittance matrix
$\theta_{i,j}$	Angle associated with $\mathrm{Y}_{i,j}$
$\mathbf{V}_{i,h}$	Voltage at bus i at hour h
$\delta_{i,h}$	Angle associated with $\mathrm{V}_{i,h}$
$I_{i,j,h}$	Current in cable (i,j) at hour h
$I_{i,j}^{max}$	Maximum current capacity in cable (i,j)
S_i^{max}	Maximum apparent power capacity in transformer (i)
c_{el_h}	Electricity price at hour (h)
$\mathbf{Cost}_{PEV}$	The average charge cost of one PEV
$\mathbf{Price}_h$	The electricity price per kWh at hour h
$\mathbf{WP}_{City}$	No. of workplaces in the city
$\mathbf{WP}_{DS}$	No. of workplaces in the DS
$\mathbf{WP}_D$	No. of workplaces in the district where the DS is located
$\mathbf{EP}_{DS}$	No. of employed individuals living in the DS

$\mathbf{EP}_D$	No. of employed individuals living in the district where the DS is located
$\mathbf{F}_{DS}$	No. of customers (families) connected to the DS
$\mathbf{F}_D$	No. of families living in the district where the DS is located
$\mathbf{VCS}_{City}$	Vehicle commuting share in the city or country
$\mathbf{VCS}_{DS}$	Vehicle commuting share in the DS
$\mathbf{V}_{City}$	No. of vehicles registered in the city
$\mathbf{V}_{DS}$	No. of vehicles registered in the DS
$\mathbf{V}^{SL}_{city}$	No. of vehicles used for shopping and leisure journeys in the city
$\mathbf{T}^{in}_{i,h}$	Indoor temperature of each house at bus i at hour h
$\mathbf{T}^{out}_{h}$	Outdoor temperature at hour h
τ	Time constant of each house
$\mathbf{R}_{eq}$	Thermal conductance of each house
$\mathbf{Cust}_i$	No. of customer at bus i
$\mathbf{T}_{min}$	Minimum indoor temperature
$\mathbf{T}_{max}$	Maximum indoor temperature
$\mathbf{E}_{var}$	Total variable energy for the reference scenario
$\mathbf{P}_{f,c}$	Power capacity for the system in case of failure in feeder f, for reconfiguration c
$\mathbf{P}^{max}_{f}$	Maximum power capacity for the system in case of a failure in feeder f, for the optimal reconfiguration

Chapter 1

Introduction

1.1 Background

The Electric Power System (EPS), as well as the transport sector, are facing major overall changes in the near future. The EPS is facing an increase of decentralized, intermittent electricity generation and changes in the electricity demand. Partially to handle these challenges, a concept called ”smart grid” was introduced. The concept can be seen as a further development of the existing EPS with increased monitoring and communication possibilities to enhance the performance of the EPS and to support additional services to consumers.

One of the major challenges the transport sector is facing is tougher legislation regarding emission levels in several countries. To reduce emissions, industry is looking into energy carriers other than fossil fuels, such as hydrogen, ethanol, DME and electricity. However, only electricity and hydrogen can be used to accomplish zero emission vehicles (ZEVs), a key requirement in several U.S states, e.g. California. Several car manufacturers have started to produce electric vehicles (EVs) and the number of EVs are steadily increasing.

Different levels of electrification of vehicles can be attained, e.g. hybrid electric vehicle (HEV), plug-in hybrid electric vehicle (PHEV) and electric vehicle (EV). The HEV does not have electricity as its primary energy carrier and electrification is used to increase the efficiency of the vehicle by regenerating energy from braking and by operate its combustion engine at higher efficiencies compared to conventional vehicles. The PHEV has the same advantages as the HEV but with a higher battery capacity and can be energized from the EPS and propelled with only electricity. The EVs do not have an internal combustion engine and can therefore only be propelled by electricity.

The main disadvantages of HEVs and PHEVs are their complex systems and increased cost compared to conventional vehicles due to the increased number of components (they need both an electric motor and internal combustion engine [1]). The drawbacks of EVs are the high cost, the short range and, for several countries, the lack of infrastructure for charging [1].

Plug-in electric Vehicles (PEVs), which refer to both PHEVs and EVs, can, as stated, be energized by the EPS and will thereby also affect the EPS. Since only a limited number of PEVs are available today, the impact on the EPS is difficult to estimate; besides, it is not certain that PEVs will gain a significant market share. However, due to the long planning horizon of the EPS it is advisable, when planning the EPS, to consider the possibility of an increased load due to PEVs. To reduce the impact on the DS, the charging of the batteries in the PEVs can be controlled in different ways. Control strategies can be enabled by the transformation to a smart grid society. However, it is important to bear in mind that these control strategies could also be applied to other electrical loads, such as space heating, laundry machines and dishwashers. To avoid inadequate strategies, it is important to incorporate these loads when formulating control strategies.

1.2 Purpose of Thesis and Contributions

The main objective of this study is to develop an approach to evaluate the impact of PEVs charging on an electric distribution system (DS). The focus of the study is on steady state conditions in the DS, such as power capacity limitations in the DS.

Different charge control strategies are designed and the impact on the DS is compared for the proposed control strategies. The control strategies could also affect how the existing electrical loads are utilized and to investigate the potential impact of the changed usage. In addition, an approach to find the optimal reconfiguration of an open loop radial DS (OLR-DS) with regard to transfer capacity is developed.

The main contributions of this thesis may be listed as follows:

- An approach to evaluate the impact of PEVs charging on an electrical distribution system, based on vehicle statistics and demographical data, for different control strategies.

- An approach to evaluate the effects on an electrical distribution system of load management of electrical heating loads in residential homes.

- An approach to find maximum capacity in an OLR-DS for different reconfiguration option in the event of loss of a feeder.

A case study of the DS in Gothenburg has been conducted using the proposed approaches.

1.3 Thesis Outline

The outline of the thesis is as follows: Chapter 2 presents an overview of the work completed on the impact of PEVs charging on the EPS, as well as load management techniques. Chapter 3 presents the proposed approach and the assumption and data used in the study. Chapter 4 presents the results of the case study and Chapters 5 and 6 present the conclusions and suggestions for future work.

Chapter 2

Plug-in Electric Vehicles and Load Management

This chapter presents part of the work conducted on the impact on the electrical power system (EPS) due to PEVs, as well as the concept of load management.

2.1 Plug in Electric Vehicles (PEV)

The first electric vehicle (EV) was designed at the same time as the internal combustion engine vehicle (ICEV), for over a century ago; however, the ICEV became the dominant transportation technology. Today, the interest in EVs has increased primarily due to legislation, environmental concerns and the issue of oil dependence. Major concerns regarding PEVs include price, short range and access to charging infrastructure [1]. The main reason for the high price is the battery and, for the PHEVs, the increased complexity of the drive train [1]. As the development and production volumes of batteries increase, the battery cost/kWh is assumed to decrease resulting in lower cost and/or longer driving rages [1]. The infrastructures for charging PEVs are expanding in several cities, both by local energy companies and by new market players. Some countries have initiated governmental programs to promote PEVs by developing a charge infrastructure.

Although PEVs have a lengthly history, they may be regarded as a relatively new area of research, especially from an EPS perspective. Since vehicle design and batteries has been seen as the major concerns regarding PEVs, most of the research has been concentrating on these topics.

One of the first papers published on the impact on the EPS due to PEVs was [2], published in 1983. The study investigated how load management of PEVs could lower peak power in the EPS. Other studies performed at that time, such as [3], stated that to avoid increased peaks in the EPS there was a need to distribute the charging to off-peak periods. However, it would take into the early 2000:s until the topic to attracted greater academic interest. Below, the reader will find a short review of the literature published regarding impacts on the EPS due to PEVs and approaches to minimize the impacts, both on a national level (EPS) and on a local level (DS).

2.1.1 Impact on the Electric Power System

Most early studies are dealing with the impact on the EPS on a national level. The results vary considerably for different countries, both because of differences in the architecture of the EPS but also due to differences in electricity consumption.

In [4] the impact of PEVs charging on the EPS in Sweden was investigated for different scenarios, with most severe scenario assuming that 80% of all vehicles in Sweden would be PEVs by 2030. This would result in increased electricity consumption of about 6%, that is about 9.5 TWh/year [4]. The total power used for charging depend on the individual charge power and the distribution of the charging in time. With one phase 230 V/10 A charging, the accumulative total power would reach a maximum of 3000 MW, which is about 10% of the installed capacity in Sweden. There might be a need to increase the capacity on a national level or alternatively to coordinate the charging to take place during off-peak hours [4].

According to [5], above 70% of American vehicles may be converted to PEVs without exceeding the existing generation capacity if the charging would be conducted during off-peak hours [5]. However, the maximal possible PEV share varies between 18 - 127% among different states [5].

According to [6], the power capacity of the Portuguese EPS may not be adequate if uncontrolled charging were conducted even for low penetration levels. The peak power would increase by about 30% for a penetration level of 17%. However, the energy consumption would only increase by about 3.2% for the same penetration level.

The installed power capacity in France would, according to [7], be about 124 GW in 2015. By charging PEVs in an uncontrolled manner, about 10% of the vehicle fleet could be supported by the EPS. If the charging were coordinated, the capacity would be enough to supply more than 70% of the vehicle fleet with electricity [7].

A couple of statements may be found in most studies; first the increased energy demand is not a major problem since the energy needed is minor in comparison with total energy consumption in most countries. Second, the generation and transmission capacities are the limiting factors when it comes to a massive introduction of PEVs. This could be solved by controlling the time when the charging would be conducted, either by legislation or by giving customers incentives to optimally adjust the timing of the charging.

From these studies it can be concluded that the impact on the EPS would likely be more severe for countries with low electricity consumption per capita than for countries with higher consumption. For countries with low electricity consumption, the EPS and generation capacity are designed for lower consumption and the added load from charging PEVs would be a larger share of the total load compared to countries with high consumption.

2.1.2 Impact on the Electrical Distribution System

Despite the capacity limitations on a national level, the regional and local effects can be even more severe if uncontrolled charging were conducted. Most countries that have been investigated would have some limitations in the DS for large penetration level.

The impact on the Spanish DS is, among others, investigated in [8], the focus being to estimate the reinforcement cost and losses in the power system for different scenarios. Two charge periods were examined, a night-time period with 85% of vehicles connected and a day-time period with 40% of vehicles connected. With 60% of the vehicles being PEVs, the investment cost ccould increase by up to 15% of the actual DS investment costs and the energy losses could increase by up to 40%.

An important aspect regarding the impact on the DS is the driving pattern. By including data for driving patterns into simulations, the results would likely be more realistic since all vehicles would not be used simultaneously [9]. In [10], the driving pattern is used as a basis for investigating the impact on a DS in Germany. The study also discusses the issue that vehicles are used for transportation and could be charged at different areas locations different hours. The results show that the effect will be most severe in the low voltage DS, however, with controlled charging, a penetration level of about 50% would be possible.

The Portuguese DS analyzed in [11] would experience problems with voltage drops at penetration levels below 10% if no controls were applied. Simulations were conducted in PSS/E and consider the average drive distance, i.e. the charge time would be calculated according to the electricity consumed/day instead of according to the size of the battery which also is important to obtain reliable results. However, instead of charging daily, the charging would take place when the battery is assumed to be empty.

A way to model driving patterns is to use stochastic modeling, which is done in [12] where a DS in Canada is investigated in a probabilistic way. The study takes into consideration that the PEVs can be charged at different locations and that charge behaviors will vary between different areas. It is assumed that the charging can be conducted at home, at work or at a retail location. The number of vehicles charging at the retail location is based on traffic volume data but how the number of PEVs being charged at the work location is not presented. The results show that for high penetration levels, there will be problems with capacity and transformer overloading. In the residential area, there might also be problems of voltage drops due to the long over head lines.

As presented above, most previous studies show that many DS would experience capacity problems if the charging were uncontrolled. However, by controlling the charging, the impact could be reduced and a larger PEV share could be incorporated. Below, different approaches for coordination or controlling the charging are described.

Different approaches can be used to limit the impact on the DS due to PEVs, e.g. [11] simulating the impact on the DS based on a system with dual tariffs and a smart charging schedule that only allows charging if the capacity would be enough. The smart charge approach has also been investigated by [13] and [14]. In [13] an optimal charge profile for a residential DS is found, based on the IEEE test feeder, by varying charge power and charge time. This is achieved by using quadratic and dynamic programming, whereby quadratic programming would be preferable due to shorter computational time and better accuracy. Three different charge periods (night, evening and day) are designed in which, for the uncoordinated charging, the charging would be randomly distributed using a charge power of 4kW. For coordinated charging, the charge power varied by between 0-4kW for the same charge periods. By stochastic programming, the load profile is varied and an optimal charge profile can be found that is valid for different load profiles. The results showed that a penetration level of 30% could not be handled without reinforcement if the charging were uncoordinated. The optimal charge profile would reduce the losses simultaneously as the voltage profile were improved. Similarly, [14] optimized the charging by minimizing the losses. However, the results were compared with other optimization algorithms, i.e. maximizing load factors and minimizing load variance. By using these algorithms, the losses stayed in the same range but the computational time would be improved.

Even though it would be beneficial for the distribution system operator (DSO) if the charging were conducted according to these smart charge algorithms, the incentives for the customer may be limited. Commonly, the idea is to let the DSO or another company control the charging and compensate the customers. Instead of letting an external party control the charging, a possible scenario would be to give customers incentives to act on the real-time electricity price [15], and thereby controlling their charging themselves.

Another way of dealing with the impact on the EPS is to use the stored energy in the batteries to support the EPS during situations of shortage. This concept is called vehicle to grid (V2G) and has been discussed over the last five years. The economic aspects of V2G are, among others, described in [16] and [17]. However, V2G will increase the cycling of the batteries and depending on how the V2G is controlled, the lifetime of the battery could be affected [17, 18]. According to [17], the cost associated with V2G is estimated to be about US$ 0.16 - 0.30/kWh, which is high compared to base load electricity generation (about US$ 0.05/kWh) [17]. The highest revenue is instead achieved if the PEV were to participate in the balance market, where not only the energy but also the power available is paid for [16]. However, the balancing market varies for different countries and it is not always beneficial to the customer to participate [19]. Usually, the bid size on the power market is high which means that several vehicles must be aggregated to provide the power needed to participate in the market [20].

To reduce the cycling of the battery, unidirectional V2G can be applied [20]. An aggregator that controls a vehicle fleet can be regulating both up and down by increasing or decreasing the charging power. However, this adds limitations on the power the aggregator can provide. Different control algorithms were presented in [20] and the results showed that optimized algorithms offer benefits to all participants.

2.2 Load Management

Electricity demand varies both by day and by year and since it is difficult to store electricity in large quantities it is produced at the same time as it is consumed. Hence, the variations in demand result in variations in the electricity generation and generation capacity must be designed to handle the peak demand. Similarly, the transmission capacity in the EPS must be designed to handle the peak power in the system. The variation in electricity demand leads to increased cost of electricity since it requires a higher transmission capacity in the EPS and since the electricity consumed during the peak is usually produced by generation plants with high production cost.

One way to reduce the variations in electricity demand is to use a load management scheme to control when electricity is used. Different load management techniques have been proposed and used, e.g. time-of-use-tariffs (TOU), interruptible load tariffs, critical peak pricing, real-time pricing (RTP) and distribution system loss reduction [21, 22]. As stated in [22] different techniques can have differential impact on the EPS.

In Sweden, different techniques have been used to control the loads, [15], such as TOU-tariffs, with one high price period and one low price period and interruptible-load tariffs. However, these contracts are today mainly available for customers with high electricity consumption. For customers with lower demand, three DSOs offer electricity tariffs where one part is based on the peak demand during the past month [15].

Chapter 3

Case Set-up

This chapter presents the proposed approach to evaluate the impact of PEVs charging on the electrical distribution system (DS) and changes in how existing loads are used for different control strategies.

In addition, this chapter includes input data and assumptions used in the case study.

3.1 The Proposed Approach

Fig. 3.1 presents a flowchart of the proposed approach.

The first step is to gather the data needed for the study. From the data, four key parameters can be processed for further analysis: i) the locations of the vehicles (i.e., where they can be charged); ii) when they are parked (i.e. when they can be charged), iii) the manageable loads and iv) technical limitations of the DS. The second step is to formulate and implement the optimization models for different control strategies. The final step is to use the data in the models developed to evaluate the impacts of different control strategies on the DS. The optimization models mentioned above are based on an AC optimal power flow framework which is described in e.g., [23], with the objective functions being: maximization of the number of PEVs, minimization of network losses, minimization of the electricity cost paid by PEVs owners, respectively. These models are implemented in a General Algebraic Modeling System (GAMS), a high-level modeling system for mathematical programming and optimization and solved using the non-linear programming solver MINOS5 [24].

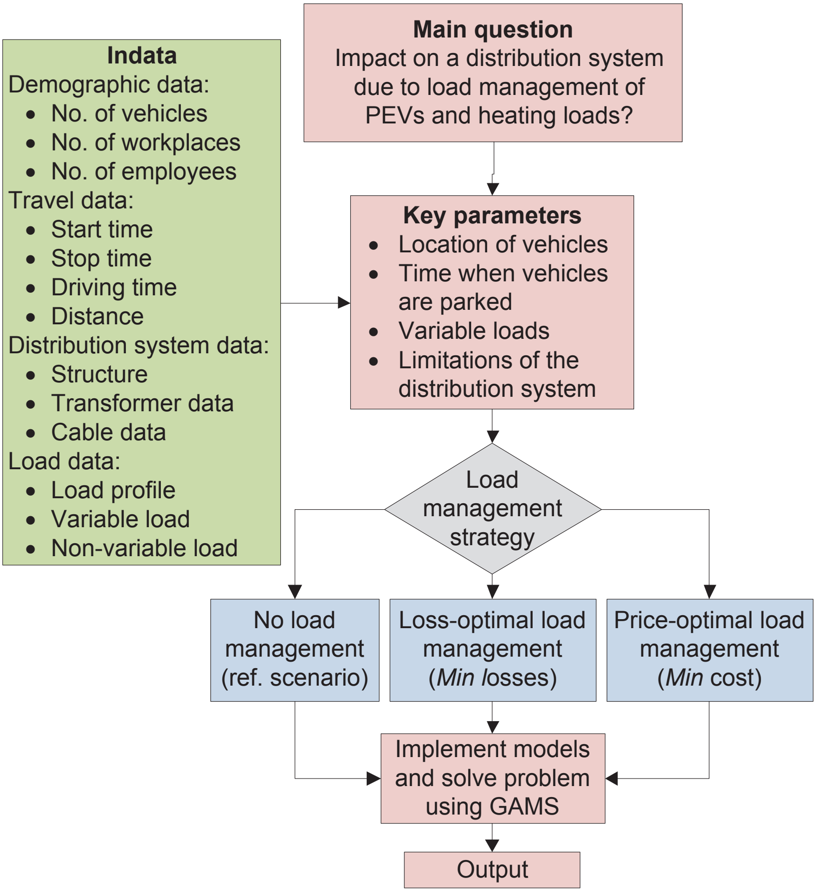

Figure 3.1: Flowchart of the proposed approach.

The main objective of this thesis is to evaluate the impact of PEVs charging on the DS. It is, however, not certain how PEVs will be used or how/when PEVs will be charged. Without any changes in the electricity market or added intelligence in the DS, it is assumed that the charging will be conducted immediately after each journey, since there are no incentives to delay the charging. As more intelligence is introduced into the DS, the possibility to control and coordinate the loads increases. This study investigates three different control strategies:

- **Uncontrolled strategy;** The charging is conducted immediately after each journey or immediately after the last journey of the day.
- **Loss-optimal strategy;** The charging is conducted to min-

imize the losses in the DS.

- **Price-optimal strategy;** The charging is conducted to minimize the electricity cost to the customers.

The *loss-optimal strategy* presents the theoretically minimum impact on the DS and is based on the forecast electricity demand. The *price-optimal strategy* assumes that the customers are charged with hourly electricity tariffs, e.g. the electricity price on the Nordic day-ahead market. Further, it is assumed that the control strategies could be applied for other non-time critical loads in the homes, such as electric heating, air conditioning, hot water etc. However, these loads (hereinafter referred to as variable loads) will be limited by constrains other than the PEV loads.

The place where the charging is conducted partly depends on the development of the charge infrastructure. At an early stage, without a developed charge infrastructure, it is assumed that the charging will be conducted mostly at home. As the charge infrastructure is getting more developed, the charging can also take place outside the home, e.g. at work or shopping malls. In this thesis, six different scenarios are investigated and compared regarding PEVs charging and changes in the use of existing loads:

- **Reference scenario:** without any PEVs.
- **Scenario A:** Charging is only conducted at home, i.e. limited charge infrastructure is available.
- **Scenario B:** Charging is conducted both at home and at work, i.e. a well-developed charge infrastructure.
- **Scenario C:** As reference scenario but with variable loads.
- **Scenario D:** As scenario A and with variable loads.
- **Scenario E:** As scenario B and with variable loads.

Although it would be possible to charge at shopping and sport centers in the future, it has been neglected in this study. The reasons to neglect this are mainly due to limited data available for Sweden regarding the location of the shopping and sport centers and how long vehicles are parked at such locations. Additionally, only privately owned cars have been considered in the case study and are hereinafter referred to as vehicles.

There are three fundamental alternative designs of a DS, radial, loop and network system [25]. The DS used in the case study is designed as an open loop radial DS (OLR-DS). An OLR-DS is designed as a looped system but is normally operated radially using the tie and sectionalizing switches. The system configuration can be modified by changing the status of the switches [26]. This will enable the possibility of improving operating condition, such as minimizing the losses but also improving the reliability of the system. The reliability is improved when the system is operated in such a way that when a failure occurs in one of the feeders, all loads can be supplied by the remaining feeders with minimum interruption time. In addition to the proposed control strategies, an approach is developed to analytically find the optimal reconfiguration, with regards to the capacity, and the maximal capacity of the system when one of the feeders is disconnected.

This section presents the formulation of the proposed control strategies developed in this study and the approach to find the maximal capacity in an OLR-DS.

3.1.1 Uncontrolled Strategy

The uncontrolled strategy assumes that the charging is conducted immediately after each journey or immediately after the last journey of the day, depending on the scenario. For all scenarios, it is assumed that the charging is conducted on a daily basis and the energy requirement depends on the distance driven and the energy consumption per kilometer.

3.1.1.1 Objective function

The objective is to maximize the number of PEVs which can be charged in the DS. This is shown in Eq. (3.1), where the decision variable is the penetration level, PEV$_{share}$.

$$PEV_{max} = \sum_{h=1}^{24} (VH_h^H + VH_h^W + VH_h^L) \cdot PEV_{share} \tag{3.1}$$

The total number of vehicles consist of all vehicles that are making a stop in the area, i.e. the vehicles commuting to the area in the morning (VH$_h^W$), i.e. commuting to work, and in the afternoon (VH$_h^H$), i.e. commuting home, and the vehicles that conduct a leisure-related journey (e.g. for shopping, exercising or visiting a friend) during the day (VH_h^L).

3.1.1.2 Constraints

The total power drawn from the DS by the PEVs depends on the active charge power (CP_P) and the charge time (CT) and is calculated from Eqs. (3.2) - (3.4). As can be seen in the last fraction in Eqs. (3.2) - (3.3), the PEVs are assumed to be distributed between the buses according to the base load power demand of each bus, and during the day according to the stop time given by [9]. For scenario A, where only charging at home is available, no PEVs will be charged at work, i.e. $\mathrm{VH}_h^W = 0$, and the charge time for the PEVs charging at home will be increased since the interval between the charges is increased.

$$P_{PEV_{i,h}}^H = \sum_{k=h-CT_H+1}^{h} (VH_k^H \cdot PEV_{share}) \cdot CP_P \cdot \frac{P_{D_{i,h}}}{\sum_{i=1}^n P_{D_{i,h}}} \tag{3.2}$$

$$P_{PEV_{i,h}}^W = \sum_{k=h-CT_W+1}^{h} (VH_k^W \cdot PEV_{share}) \cdot CP_P \cdot \frac{P_{D_{i,h}}}{\sum_{i=1}^n P_{D_{i,h}}} \tag{3.3}$$

$$P_{PEV_{i,h}}^L = \sum_{k=h-CT_L+1}^{h} (VH_k^L \cdot PEV_{share}) \cdot CP_P \cdot \frac{P_{D_{i,h}}}{\sum_{i=1}^n P_{D_{i,h}}} \tag{3.4}$$

The total power drawn from the DS to charge the PEVs is calculated through Eq. (3.5) and Eq. (3.6):

$$P_{PEV_{i,h}} = P_{PEV_{i,h}}^H + P_{PEV_{i,h}}^W + P_{PEV_{i,h}}^L \tag{3.5}$$

$$Q_{PEV_{i,h}} = P_{PEV_{i,h}} \cdot \tan\varphi \tag{3.6}$$

The charge time (CT) depends on the active charge power (CP_P), the efficiency of the charger and battery (η), the energy consumed per km ($Cons$) and the distance driven ($Dist$), which vary between commuting journeys and leisure journeys and is given by Eq. (3.7):

$$CT = \frac{Dist \cdot Cons}{CP_P \cdot \eta} \tag{3.7}$$

It is assumed that the distance to/from work is equal but different than the distance for leisure journeys, i.e. $CT_W = CT_H \neq CT_L$.

The standard power flow constraints are given by Eqs. (3.8) and (3.9) [23]:

$$P_{i,h} - (P_{i,h}^{base} + P_{i,h}^{var} + P_{i,h}^{PEV}) = \sum_{j=1}^{n} |Y_{i,j}||V_{i,h}||V_{j,h}| \cos(\theta_{i,j} + \delta_{j,h} - \delta_{i,h}) \quad (3.8)$$

$$Q_{i,h} - (Q_{i,h}^{base} + Q_{i,h}^{var} + Q_{i,h}^{PEV}) = -\sum_{j=1}^{n} |Y_{i,j}||V_{i,h}||V_{j,h}| \sin(\theta_{i,j} + \delta_{j,h} - \delta_{i,h}) \quad (3.9)$$

The variable load ($\mathrm{P}_{i,h}^{var}$), e.g. heating, hot water boilers etc., is constant for the uncontrolled strategy since no control strategy is applied on the load and the base load, $\mathrm{P}_{i,h}^{base}$, and variable load, $\mathrm{P}_{i,h}^{var}$, is equal to the load forecast, $\mathrm{P}_{D_{i,h}}$, in the reference scenario.

Further the voltage is limited according to Eq. (3.10):

$$0.9 \leq |V_{i,h}| \leq 1.1 p.u \quad (3.10)$$

the current limitations in the cables according to Eq. (3.11):

$$I_{i,j,h} \leq I_{i,j}^{max} \quad (3.11)$$

and the transformer capacity according to Eq. (3.12):

$$\sqrt{(P_{i,h}^{base} + P_{i,h}^{var} + P_{i,h}^{PEV})^2 + (Q_{i,h}^{base} + Q_{i,h}^{var} + Q_{i,h}^{PEV})^2} \leq S_i^{max} \quad (3.12)$$

The total loss in the DS during one day is calculated by Eq. 3.13, [23]:

$$P_{Loss} = \frac{1}{2} \sum_{h=1}^{24} \cdot (\sum_{j=1}^{n} \cdot \sum_{i=1}^{n} G_{i,j} \cdot (|V_{i,h}|^2 + |V_{j,h}|^2 - 2 \cdot |V_{i,h}| \cdot |V_{j,h}| \cdot \cos(\delta_{j,h} - \delta_{i,h}))) \quad (3.13)$$

The charge cost and the cost of the variable loads during one day are calculated according to (3.14):

$$Cost = \sum_{h=1}^{24} (Price_h \cdot \sum_{i=1}^{n} (P_{i,h}^{var} + P_{i,h}^{PEV})) \quad (3.14)$$

and the average cost of charging one PEV during a day is calculated according to Eq. (3.15):

$$Cost_{PEV} = \frac{\sum_{h=1}^{24} Price_h \cdot \sum_{i=1}^{n} P_{PEV_{i,h}}}{PEV_{max}} \tag{3.15}$$

It can be noted that the loss and cost can be calculated for any given PEV penetration. The time step of the simulations in this study is one hour. It can be reduced, if desired, to gain more detailed results.

3.1.2 Loss-Optimal Control Strategy

Compared to the *uncontrolled strategy* where the charging immediately starts when a vehicle is parked, the *loss-optimal control strategy* seeks to conduct the charging when it is most favourable from the DSO's point of view. The objective of the *loss-optimal control strategy* is to minimize the losses in the DS for a given penetration of PEVs. The objective function is given by Eq. (3.13). The decision variables for the *loss-optimal control strategy* are the total charge power at hour h, i.e. when the charging is conducted, and the variable load at hour h.

3.1.2.1 Constraints

The objective function is subjected to the number of PEVs given by Eq. (3.1) and, as for the *uncontrolled strategy*, to the total power used for charging, power flow constraints and network constraints given by Eqs. (3.5) - (3.12). However, the total power used for charging will be limited by the number of PEVs that are parked according to Eqs. (3.16) - (3.18):

$$P_{PEV_{i,h}}^{H} \leq VH_h^{HP} \cdot \frac{P_{D_{i,h}}}{\sum_{i=1}^{n} P_{D_{i,h}}} \cdot PEV_{share} \cdot CP_P \tag{3.16}$$

$$P_{PEV_{i,h}}^{W} \leq VH_h^{WP} \cdot \frac{P_{D_{i,h}}}{\sum_{i=1}^{n} P_{D_{i,h}}} \cdot PEV_{share} \cdot CP_P \tag{3.17}$$

$$P_{PEV_{i,h}}^{L} \leq VH_h^{LP} \cdot \frac{P_{D_{i,h}}}{\sum_{i=1}^{n} P_{D_{i,h}}} \cdot PEV_{share} \cdot CP_P \tag{3.18}$$

In addition, all PEVs connected to bus i need to be charged over 24 hours, according to Eqs. (3.19) - (3.21):

$$\sum_{h=1}^{24} P^{H}_{PEV_{i,h}} = \sum_{h=1}^{24} VH^{H}_{h} \cdot \frac{P_{D_{i,h}}}{\sum_{i=1}^{n} P_{D_{i,h}}} \cdot PEV_{share} \cdot CP_P \cdot CT_H \quad (3.19)$$

$$\sum_{h=1}^{24} P^{W}_{PEV_{i,h}} = \sum_{h=1}^{24} VH^{W}_{h} \cdot \frac{P_{D_{i,h}}}{\sum_{i=1}^{n} P_{D_{i,h}}} \cdot PEV_{share} \cdot CP_P \cdot CT_W \quad (3.20)$$

$$\sum_{h=1}^{24} P^{L}_{PEV_{i,h}} = \sum_{h=1}^{24} VH^{L}_{h} \cdot \frac{P_{D_{i,h}}}{\sum_{i=1}^{n} P_{D_{i,h}}} \cdot PEV_{share} \cdot CP_P \cdot CT_L \quad (3.21)$$

As described earlier, part of the loads can be shifted in time. For the *uncontrolled strategy*, the variable load ($P^{var}_{i,h}$) was not shifted since no control strategy was applied. For the *loss-optimal strategy*, the variable load can be shifted in time to reduce the stresses on the DS. However, since only heating loads have been assumed to be variable in this study, the temperature inside the houses will vary. The temperature will mainly depend to the outside temperature, T^{out}_{h}, the thermal conductance of the building, R_{eq}, and the time constant of the building τ and can be expressed, in simplified form, as in (3.22):

$$T^{in}_{i,h} = e^{\frac{-1}{\tau}}(T^{in}_{i,h-1} - \frac{P^{var}_{i,h-1}}{R_{eq}} + T^{out}_{h}) + \frac{P^{var}_{i,h-1}}{R_{eq}} + T^{out}_{h} \quad (3.22)$$

$P^{var}_{i,h}$ is limited to the installed capacity of the heating system in the houses expressed by (3.23):

$$0 \leq P^{var}_{i,h} \leq cust_i \cdot 4.5kW \quad (3.23)$$

the temperature must stay within the allowed temperature range according to (3.24):

$$T_{min} \leq T^{in}_{i,h} \leq T_{max} \quad (3.24)$$

and the energy used should be the same as for the reference scenario, as (3.25):

$$E_{var} = \sum_{i=1}^{n} \sum_{h=1}^{24} P_{i,h}^{var} \tag{3.25}$$

The maximum penetration can be found by iteratively increasing the penetration level until any of the limitations in the DS are violated.

3.1.3 Price-Optimal Control Strategy

Although the losses can be reduced by charging according to the *loss-optimal control strategy*, the incentive for the customer may be limited [27]. The introduction of smart meters enables the possibility to pay the electricity on an hourly basis. In the *price-optimal control strategy*, it is assumed that the electricity tariffs for the customers are based on the spot price at Nordpool spot. The *price-optimal control strategy* seeks to minimize the electricity cost for the customers according to Eq. (3.14). Similarly to the *loss-optimal control strategy*, the decision variables for the *price-optimal control strategy* are the total power used for charging and the variable load at each hour h.

3.1.3.1 Constraints

The objective function is subjected to the number of PEVs given by Eq. (3.1), the total power used for charging, power flow constraints, the distribution of the PEVs according to Eqs. (3.5) - (3.9) and Eqs. (3.16) - (3.21) and the variable load according to Eqs. (3.22)-(3.25) .

Since this control strategy is customer oriented (i.e., the customers decide when to charge or use the electricity) and the customers are unaware of the limitations in the DS (Eqs. (3.10) - (3.12)), these limitations will not affect the timing of the charging although it will limit the penetration level of PEVs. Therefor, these constraints are not included in the *price-optimal control strategy*. However, the maximum penetration of PEVs is found by iteratively increasing the penetration level until any of the limitations in the DS (Eqs. (3.10) - (3.12)) are violated.

3.1.4 Open Loop Radial Distribution Systems

The power capacity in a DS is either limited by the thermal limit of cables and transformers or by the voltage drop in the DS. The same holds for the OLR-DS. However, in an OLR-DS with high level of reliability, all loads could be supplied even in the event of a failure in a feeder. Since the remaining feeders must be able to supply all loads the maximum loading of the cables is reduced to maintain this high level of reliability. Several studies, e.g. [26, 28, 29], have been conducted to find the optimal reconfiguration of an OLR-DS. However, the focus of these studies has been on minimizing the losses and the restoration time, not to maximize the capacity or reliability of the system [26]. As the demand for electricity increases, e.g. by the introduction of PEVs, it becomes more important to operate the DS in an efficient manner and to know the limitations of the DS.

Due to the non-linear nature of the power flow problem and the large number of reconfiguration possibilities, it is difficult to find the solution that provides the highest capacity. To find the reconfiguration option with highest power capacity in case of a disconnected feeder, an analytic approach is proposed. Fig. 3.2 presents the proposed approach. First, all reconfiguration possibilities (c) in case of the most severe fault (i.e. a fault located at one of the main feeders (f)) are identified. Second, the total maximum power of the DS ($\mathrm{P}_{f,c}$) is calculated for each reconfiguration (c) by increasing the load at every substation until the DS becomes overloaded, either by the thermal limits of the cables and transformers or by the voltage drop in the system, and the reconfiguration with highest power capacity (P_f^{max}) is found. The load is assumed to be increased linearly between the substations, i.e. a substation with high load today is assumed to have a higher increase than that of a substation with lesser load. The power capacity is found when each of the feeders is disconnected, one at a time. The disconnected feeder where the lowest total power capacity of the DS is found (P_f^{max}) corresponds to the most severe fault in the DS.

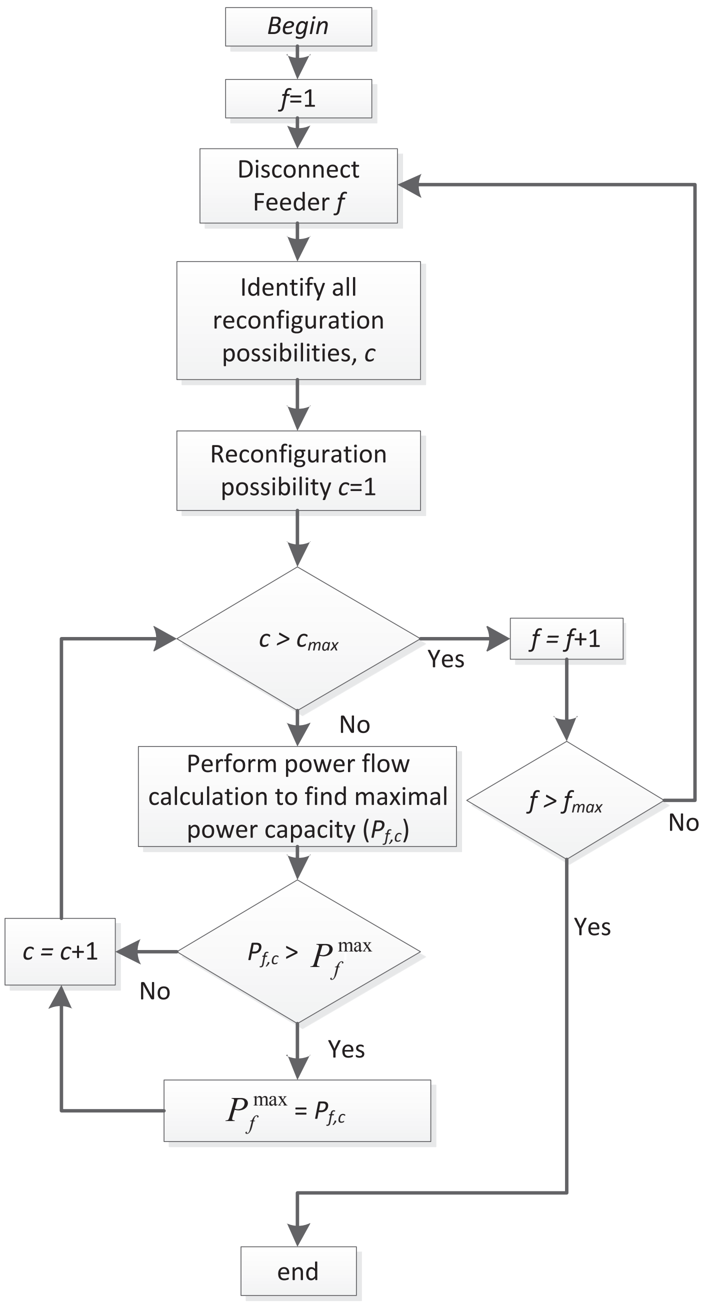

Figure 3.2: Flowchart of the process to find the optimal reconfiguration possibility and the maximal capacity.

3.2 Assumptions and Data for the Case Study

Several assumptions and data are needed to obtain reliable results regarding the impact of PEVs charging on the DS. This thesis includes a case study investigating the impact of PEVs charging in two different parts of the real DS in Gothenburg, one commercial and one residential part. This section presents data for the DS, vehicle usage data and detailed data for the electricity consumption.

3.2.1 Electrical Distribution System in Gothenburg

There are five power plants within Gothenburg, the largest plant, Rya Verket, can supply about 30% of the electricity consumed in Gothenburg [30]. The electricity that is not produced inside Gothenburg is feed in through five feed-in points. In total, there are about 18 130/10 kV transformer stations in the system and the DS consists to a large extent of underground cables. Although there are some other voltage levels in the DS, such as 20 kV and 50 kV, the voltage level is mainly 10 kV. As stated earlier, the 10 kV DS is designed as an OLR-DS, which allows the DSO, Göteborg Energi, to operate the DS with a high reliability since the DS could be restored by topology changes in case of failure in any feeder. At the customer site the voltage level is 400 V. However, some of the large industrial customers are connected directly to the 10 kV DS.

The case study focuses on the 10 kV DS although the proposed approach could be applied on the low voltage distribution system (LV-DS). The reason for not including the LV-DS is mainly due to limited data regarding the load profile of the LV-DS and since the stochastic behavior of the customers are more prominent for smaller systems (such as a LV-DS). However, the LV-DS has been studied within this project but with another approach, presented in [31]. The result indicate that the impact of PEV charging will be more prominent on the 10 kV DS than on the LV-DS in Gothenburg.

Below the two parts of the DS investigated in this thesis are described.

3.2.1.1 Commercial Area

The DS in the commercial area investigated consist of four feeders, nine 10/0,4 kV substations and two 10 kV substations. Fig. 3.3 presents the structure of the distribution system under normal operation. As can be seen, the DS is designed as an OLR-DS and can be reconfigured in case of a failure in any of the feeders.

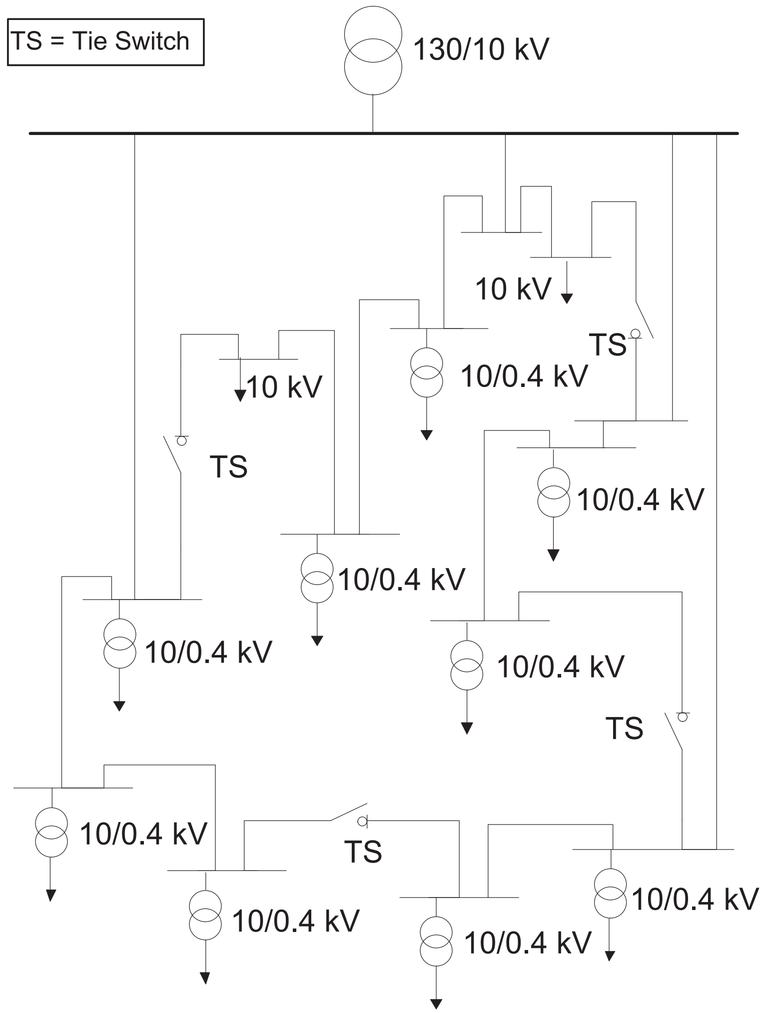

Figure 3.3: 10 kV DS in a commercial area in Gothenburg.

For this study, historical load data from 2008 have been used as forecast power demand. Fig. 3.4 presents the load profile for the year 2008 and for a peak day in 2008. As can be seen, the load varies both during the day and during the year and the peak power occurs in the middle of the day. Since the DS must be designed to withstand the highest peak load, a day with high peak demand was chosen as a reference scenario for the case study. The dips shown in Fig. 3.4, is due to missing load data.

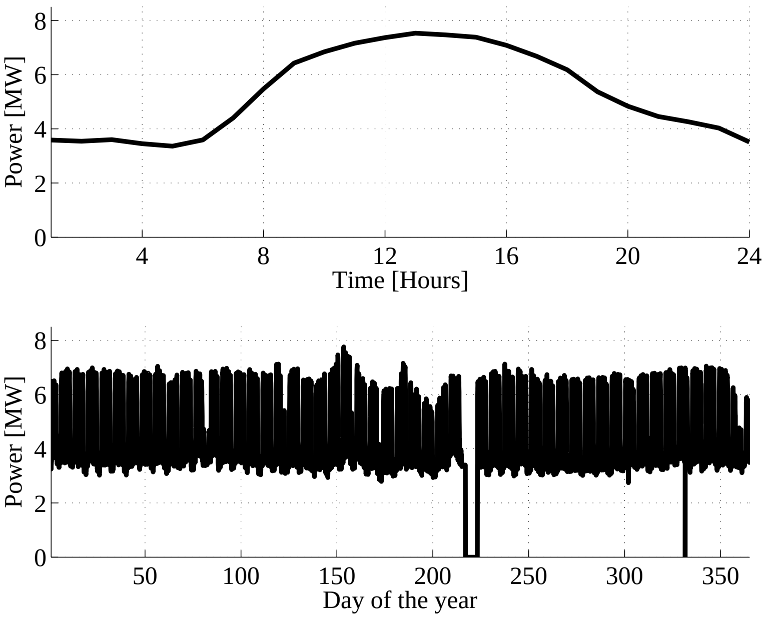

Figure 3.4: Load profiles for the peak day and for a year (2008), for the commercial 10 kV DS.

The commercial area investigated in this case study is not a pure commercial area and the DS serves both commercial and domestic customers, who live in apartments in this area. Although the majority of the electricity is consumed by the commercial customers, the number of domestic customers is higher. Several apartments can be served from the same contract and only the number of contracts are available from Göteborg Energi. Due to this, the number of domestic customers has been estimated based on the power level of the contract, i.e. a house with a contract of 160 A is assumed to serve 10 apartments. The interest in number of domestic customers is due to the usage of demographical data and will be described further in section 3.2.2. The number of domestic customers connected to the DS was estimated to be 635.

3.2.1.2 Residential Area

The DS in the residential area investigated consists of three 10 kV feeders and 26 10/0.4 kV substations. Fig. 3.5 presents the structure of the DS under normal operating conditions. Similar to the DS in the commercial area, this DS is designed as an OLR-DS.

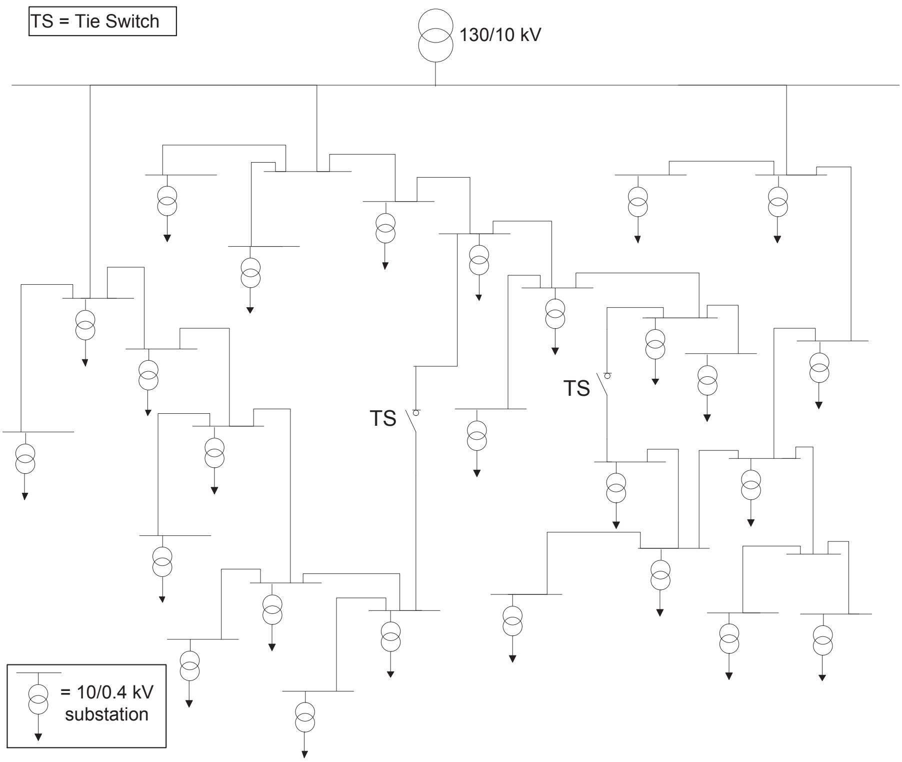

Figure 3.5: 10 kV DS in a residential area in Gothenburg.

Fig. 3.6 presents the load profile for the residential area in 2008. Similarly to the commercial area, the load data are missing for certain days. Compared to the commercial area, the peak load occurs in the afternoon and in the morning hours. This is due to the fact that the customers in this area mostly are small houses. Similarly to the commercial area, a day with peak demand was chosen for the reference scenario. The number of domestic customers in this area was estimated to be 1932.

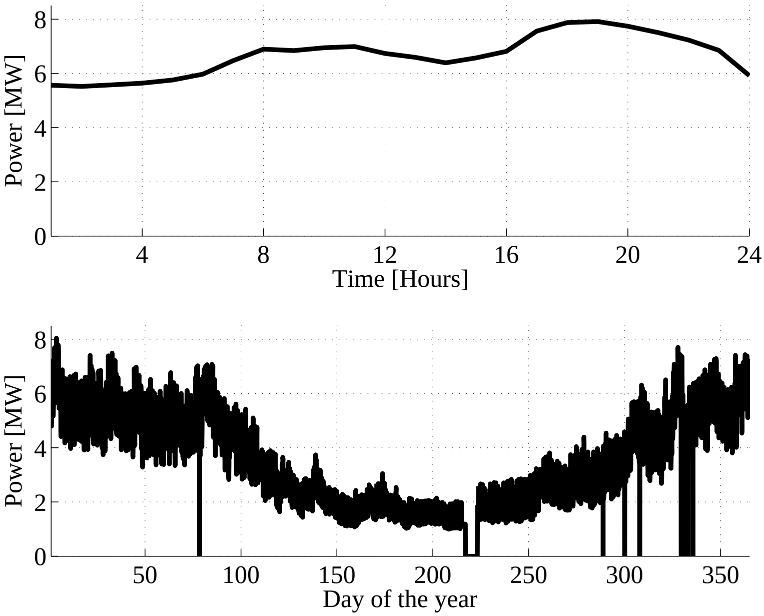

Figure 3.6: Load profiles for the peak day and for a year (2008), for the residential 10 kV DS.

3.2.2 Estimated Number of Vehicles and Their Usage

To make realistic estimations on the impact of PEVs on a DS, aspects such as how the PEVs are used and where/when they are parked are important. Since only a limited number of PEVs are in use today, the data available regarding their usage is limited. In addition, vehicle usage varies for different countries. Due to this, it is assumed that the PEVs are used similarly to the vehicles used today.

Further, technical parameters such as energy consumption and charge power are important. This section presents the assumptions and parameters, regarding PEVs and their usage, used in the case study.

3.2.2.1 Driving Behavior

In this study, the driving behavior was extracted from a national travel survey from 2006. The survey covered all movement conducted during a day, with different kind of transportation means. It includes start time, stop time, distance driven, purpose of the journey etc. [9]. Even though the survey includes much of the data needed, the survey is collecting the movement of individuals and not vehicles, this means that there is no information about how frequently each vehicle is used, e.g. twice every day or every second day. For this study, each journey was assumed to be conducted by a unique vehicle, if not the total number of vehicles in the area were exceeded. Since this will increase the number of vehicles that can be charged simultaneously, the possible impact on the power system would also be increased.

The travel survey is based on 27,000 interviews which corresponds to a response frequency of 68%. The survey divids the journeys into main journeys and partial journeys. A main journey is the main reason for the journey and can consist of several partial journeys, e.g. leaving the children at the daycare on the way to work or stopping at a shopping mall on the way home from work. In this study, only main journeys are considered.

The number of journeys and purpose of the journey varies by weekend and weekday. Since the power demand normally is higher on weekdays than on weekends, only journeys conducted during weekdays are considered in the case study. In addition, the vehicle usage is higher on weekdays than on weekends [9].

The distance driven depends on the purpose of the journey, e.g. work-related and leisure-related journeys. The average driving distance for a large city in Sweden was extracted from the national survey and were 24 km for work related journeys and 30 km for other journeys. The majority of the "other journeys" are shopping and leisure-related and are hereinafter referred to as leisure-related journeys.

Fig. 3.7 presents the start- and stop-time for journeys conducted by cars during weekdays depending on the purpose of the journey. As can be seen, most work-related journeys start around 7-8 and 16-17, while leisure-related journeys are usually conducted during the afternoon.

3.2.2.2 Estimated Number of Vehicles

According to [32], the number of registered vehicles in the city of Gothenburg are around 150 000. The distribution of the vehicles between different areas depends mainly on the number of people

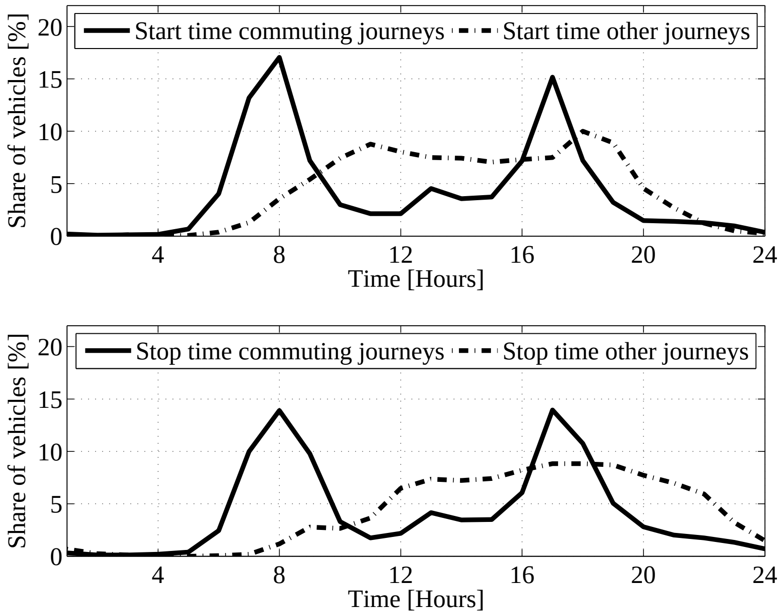

Figure 3.7: Distribution of start and stop time for different journeys.

living in the area but also on the type of area. Since vehicles are mainly used for transportation, a PEV registered in a district may be charged in other districts if a charging infrastructure is available. It was extracted from the national travel survey ([9]) that 29% of all commuting journeys in the large cities of Sweden are conducted by vehicles, consequently, during daytime these vehicles might be situated in another part of the city. Due to this, it is important to know in what kind of area the DS is located. For this study, the number of domestic customer connected to the DS is estimated and the location of the DS is known. In addition, demographical data, such as number of vehicles, workplaces and families are available for the district in which the DS is located.

The number of individuals working in the DS (WP$_{DS}$) and the number of employed individuals living in the DS (EP$_{DS}$) can be calculated according to (3.26) and (3.27) respectively.

$$WP_{DS} = \frac{WP_D \cdot F_{DS}}{F_D} \tag{3.26}$$

$$EP_{DS} = \frac{EP_D \cdot F_{DS}}{F_D} \tag{3.27}$$

However, as shown above, all commuting journeys to work are not conducted by car. By using the vehicle commuting share (VCS), i.e. the percentage of all work-related journeys that are conducted by car in the city, the number of vehicle commuting to its work inside the area can be calculated according to (3.28) and the vehicles commuting back home to the area according to (3.29).

$$VH^{W} = WP_{DS} \cdot VCS_{City} \tag{3.28}$$

$$VH^{H} = EP_{DS} \cdot VCS_{DS} \tag{3.29}$$

Due to differences in vehicle density (i.e. number of vehicles/individual) between the districts, it is assumed that VCS varies by district and also by DS, i.e. the number of individuals commuting by car will probably be higher for a district with high vehicle density than for a district with lower vehicle density. The VCS for the DS (VCS$_{DS}$) is calculated according to Eq. (3.30)

$$VCS_{DS} = VCS_{City} \cdot \frac{VH_{DS} \cdot EP_{City}}{EP_{DS} \cdot VH_{City}} \tag{3.30}$$

Although many journeys are work-related, there are journeys conducted for other purposes, such as shopping and leisure-related journeys. The number of vehicles used for these journeys can be calculated according to Eq. (3.31). With a developed charge infrastructure, these vehicles could be charged while they are parked, e.g. at a shopping center. However, due to limited data, it is assumed that they are charged at home for all scenarios.

$$VH^{L} = \frac{VH^{L}_{city} \cdot VH_{DS}}{VH_{city}} \tag{3.31}$$

Table 3.1 presents the number of vehicles, families, employees, workplaces etc. for the commercial and residential districts investigated in the case study, as well as for the city of Gothenburg. The data are derived from [9] and [32].

From (3.26) - (3.31) and the data in Table 3.1, the same information can be calculated for the DSs investigated. Table 3.2 presents the data for the DSs investigated in this case study.

The number of vehicles (VH$_{DS}$) in Table 3.2 is the total number of vehicles registered in the area. VH^{W} and VH^{H} are the number of vehicles commuting to/from an area during a day. As shown in Fig. 3.7, all vehicles are not starting their journey simultaneously.

Table 3.1: Demographical data.

	Residential district	Commercial district	City of Gothenburg
No. of families (F_D)	2 381	3 967	286 195
No. of employees (EP_D)	3 409	3 301	241 450
No. of workplaces (WP_D)	581	13 408	293 509
No. of vehicles (VH_D)	2 842	1 587	148 547
Vehicle Commuting Share (VCS)	39.4%	22.7%	29.1%
No. of vehicles used for leisure journeys (VH^L_{city})	—	—	89 867

Table 3.2: Distribution system data.

	Residential DS	Commercial DS
No. of customers (F_{DS})	1 932	635
No. of employees (EP_{DS})	2 766	528
No. of workplaces (WP_{DS})	471	2 146
No. of vehicles (VH_{DS})	2 306	254
Vehicle Commuting Share (VCS_{DS})	39.4%	22.7%
No. of vehicles used for leisure journeys (VH^L)	1 395	154
No. of vehicles commuting to work in the DS (VH^W)	137	624
No. of vehicles commuting home to the DS (VH^H)	1 091	120

Since the number of vehicles commuting to/from an area varies, the stop time of the commuting journeys are divided into two parts, one for vehicles commuting to work inside the area (V^W), i.e. vehicles that are remaining in the area during the day, and one for vehicles commuting home to the area (VH^H), i.e. vehicles that are remaining in the area during the night. Further, it is assumed that all vehicles are parked at home by midnight. Fig. 3.8 presents the stop time for the residential and commercial area investigated in this study.

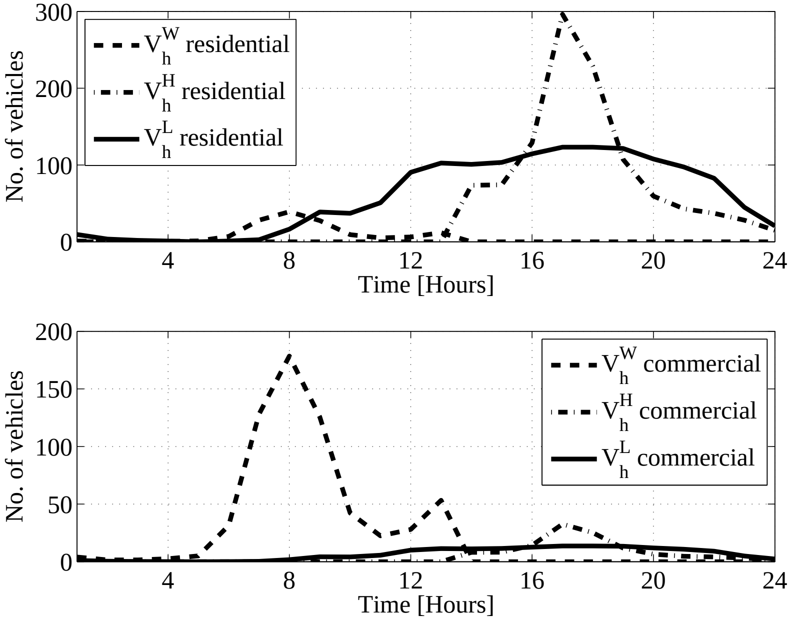

Figure 3.8: Stop time for the vehicles in the simulated areas.

Since a vehicle is only situated in a location for a certain time, it can only be charged during this period. similarly to the stop time distribution, the start time distribution, shown in Fig, 3.7, can be divided into two parts. From this, the possible charge time for the loss-optimal and price-optimal control strategies can be derived. Fig. 3.9 presents the possible charge time for both areas.

3.2.2.3 PEV Parameters

Beyond the driving behavior and number of vehicles, the energy consumption is an important aspect. The energy consumption depends mainly on the size of the vehicle and can vary between 0.1-0.3 kWh/km [33]. For the case study, an average energy consumption of 0.2 kWh/km was assumed.

Another aspect, that will affect both the charge time and the impact on the DS, is the charging power. Today, there are no standards regarding the charge power. The charge power will depend on the power rating of the onboard charger, the available

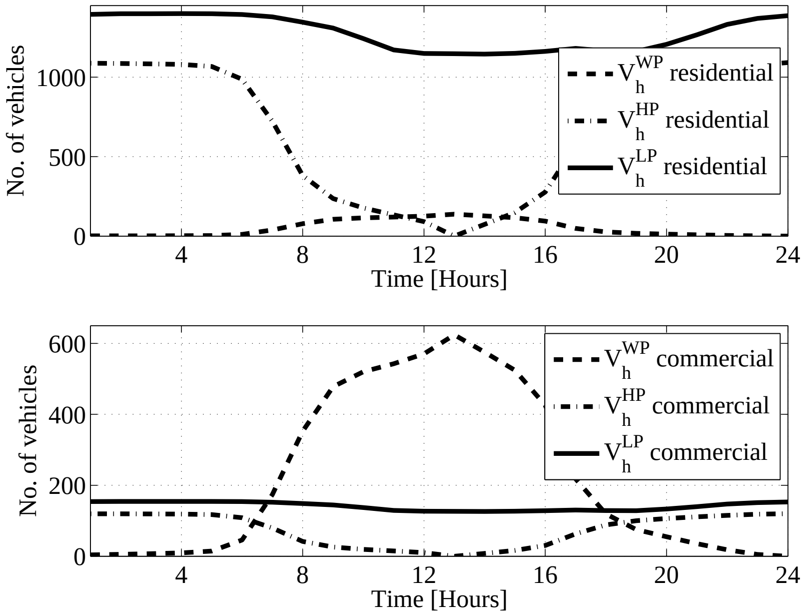

Figure 3.9: Number of used vehicles that are parked.

power at the plug and the State of charge (SOC) of the battery. For low SOC, the charge power is more or less constant but decreases as the battery gets more and more charged. However, for a fully discharged battery, most of the energy is delivered to the battery during the constant charge power period [34,35] and a constant charge power has been used in this study. Most single family homes in Sweden has at least a three phase 400 V 16 A or 20 A connection available. The majority of the charge pools available today can charge with a power of at least 3.68 kVA [36]. Similarly, the onboard charger in most of the PEVs being produced today have the possibility to charge with, at least, a power of 3.68 kVA (230 V/16 A) [33, 37, 38]. Based on this, a charge power of 3.68 kVA was assumed in this work.

Transferring power from the DS to the batteries involves losses both in the charge equipment and in the battery itself. For slow charging, the charger is usually a AC/DC converter that controls the power to the batteries. When the charger starts to charge the battery, it charges at constant current and when it reaches the full capacity, it charges at constant voltage [35]. Accordingly, the power drawn from the DS will vary during the charge cycle. Similarly, since the operating point of the charger varies, the efficiency of the charger will also vary [39]. The losses in the batteries depends mainly on the resistance in the batteries and increases with an increased charge power. However, since the charge power is assumed to be constant, the efficiency would also be constant and, as in [13], an overall efficiency of 88% is assumed in this study.

The power factor of a battery charger depends on how it is designed and controlled. Although the charging can be conducted close to unit power factor [40, 41], a power factor of 0.95 was assumed in this study. This would likely increase the impact on the DS, due to the increased apparent power drawn from the DS and the increased charge time. In addition, the reactive power will have a large impact on the voltage level in the DS. Table 3.3 presents the assumptions made for the case study.

Table 3.3: Vehicle and charge parameters.

Energy consumption	0.2 kWh/km
Charge power	3.68 kVA
Power factor	0.95
Charge efficiency	88%

3.2.3 Load Management in Domestic Homes

As stated above, the control strategy applied to the PEVs charging can also be applied on other loads in the home. However, the consumer would probably not want to change all his/her electricity consumption, e.g. some loads, such as cooking and lighting, are more critical than other loads, such as heating and laundering. In this study, it has been assumed that parts of the electricity used for space and tap-water heating can be shifted in time without causing inconvenience to customers.

A large part of the electric energy consumed in a detached house in Sweden is used for heating purposes. About 25% of all detached houses in Sweden are heated with electricity, either by direct electricity or by an air-air heat-pump [42]. The electricity consumed for heating purposes in detached houses was, in 2008, 12.9 TWh [42], about 8% of the total electricity consumption in Sweden. Since most of the heating is consumed during the cold winter months, which is, when electricity demand is highest for most of Sweden, this indicates a great potential for reducing peak power demand.

This section presents the data and assumptions made to investigate the impact on the residential DS by applying the proposed control strategies on the existing loads in the DS.

3.2.3.1 Variable Loads

To find the potential load that are variable, i.e. that are possible to alter in time, without reducing the comfort level of the customers, a national metering campaign conducted by the Swedish Energy Agency is used [43]. The campaign measured all individual loads at 400 households in Sweden, both apartments and single houses. From the data, an average load profile was extracted for each load for a winter month [44]. The loads were then divided into base and variable load. The variable loads consist of space heating and tap water heating. Other loads, such as laundry machines and dishwashers, could be considered but due to the low energy consumption compared to the heating loads and the inconvenience for the customer, it was not included in the variable load. Fig. 3.10 presents the load profile derived from the metering campaign divided into base and variable load.

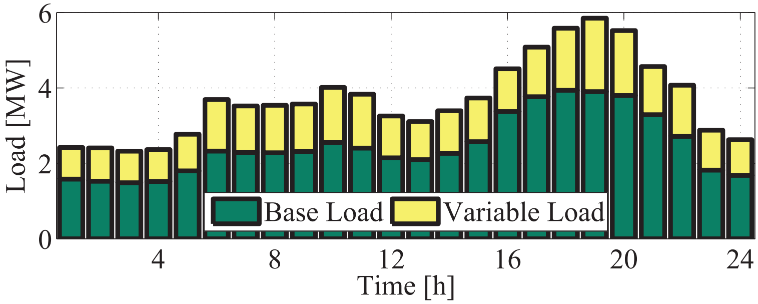

Figure 3.10: Load profile for variable and non-variable (base) loads, from the metering campaign [43].

From the load profile in Fig. 3.10, the percentage of the load that was variable, i.e. used for space and tap water heating, was calculated for each hour. The same percentages were applied on the load profile for the residential DS, shown in Fig 3.6. Fig. 3.11

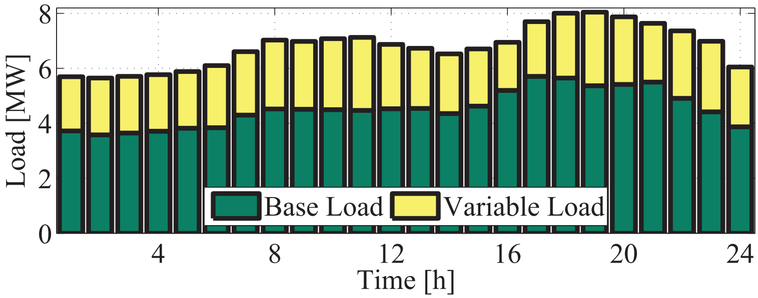

Figure 3.11: Load profile for the residential area, divided into variable and non-variable (base) loads.

presents the resulting profile, which is used for the load management model. As can be seen, a significant share of the total load is variable, the variable load varying between 25-35% of the total load. This means that the peak power could in theory be reduced by at least 25% provided that the load valleys are large enough to handle the shifted energy without causing new power peaks.

To avoid inconvenience for customers, the indoor temperature was limited to 21 ± 1.5°C. According to [45], the indoor temperature can vary from 20°C to 24°C with maintained comfort of the residents and some real estate owners reduce the temperature to 18°C during the night. The indoor temperature in a building depends mainly on the outdoor temperature, the isolation and time constant of the building and the heat generated in the building. For the simulations, a constant outdoor temperature of -14.6°C is assumed, which is the lowest temperature that the heat system should be design to handle in Gothenburg [46]. A low outdoor temperature was chosen to assess the load management potential in a restrictive manner.

For a typical single family house with low heat capacity, the time constant varies between 24-48 hours and for a house with large heat capacity, the time constant can be above 100 hours [47]. A higher time constant will lead to slower changes in the indoor temperature. For the case study, an average time constant of 40 hours has been assumed to assess the load management potential in a restrictive manner. The time constant depends both to the thermal resistance and to the heat capacity of the building. Based on the time constant and the average energy used for heating for each house (calculated from Fig. 3.11) the thermal conductance was calculated to be 32 W/K and the heat capacity of the building to be 4608 kJ/K. For a standard house in Sweden these values are usually higher. The reason for the low values used in the simulations are due to the low outdoor temperature and energy consumption assumed.

In addition to indoor temperature, the power used for heating cannot exceed the capacity of the installed heating equipment in the houses. The Swedish Building Regulation (BBR) introduced in 2010, limits on the maximum installed electric power used for heating [46]. The capacity was limited to 4.5 kW for new houses. Most buildings in the area are built before 2010 and are not affected by the regulations. However, to assess the load management potential in a restrictive manner, the maximum installed electric heating capacity was limited to 4.5 kW/house in this study.

The energy used for tap water heating is about 10% of the total variable load, i.e. 90% of the variable energy is used for space heating and 10% tap water heating. In reality, the constraint on the electrical power used for tap water will mainly be limited by the electrical power of the heater, the size of the water tank and the usage of the hot water. However, in this thesis tap water heating is treated as a part of the space heating. This is mainly due to limited data and due to the fact that hydronic heating system is commonly used in Sweden, which serves both tap water and space heating [48].

By reducing heat production in afternoons, the system could account for the excessive heat produced by cooking etc. resulting in a more even indoor temperature and reduced energy usage [49]. For houses with heat pumps, energy usage can also be reduced by operating the device more efficiently [49]. This is, however, not taken into consideration in this thesis and the heat demand is assumed to remain at the same level as in the reference scenario, i.e. if the heat system is turned off for a time, the system operates at a higher power when it is turned on again to keep the energy demand for a 24 hours period at the same level as in the reference scenario.

3.2.4 Electricity Price at Nordpool Spot Market

Although the electricity in Sweden is traded on an hourly basis at the Nordic electricity market (Nordpool spot), most residential customers have their electricity price based on either monthly average price or fixed yearly contracts.

Customers are obliged to pay a network tariff. Usually, this is a fixed price per kWh but a few companies include a power tariff to reduce the maximum peak power consumption [15]. In addition to electricity and network cost, the price of an electricity certificate (around 0.06 SEK/kWh) and an electricity tax (0.283 SEK/kWh) is added, plus a value-added tax (25%) [50].

In this thesis, it is assumed that customers may chose to have the electricity tariff based on the hourly day-ahead spot-prices at Nordpool spot, [51]. The Nordpool spot prices depends both on the consumption and production, with variations reflected in the price. In this thesis, it is assumed that, on a large scale, the number of customers using time-based tariffs are small, resulting in minor differences in the total electricity consumption. However, the number of customers using the tariffs locally can be high.

A reason to introduce dynamic electricity tariffs based on the electricity spot price is to support the introduction of intermittent, renewable electricity generation. With this type of tariff, the consumption of electricity will increase when it is cheaper, i.e. when there is a surplus of electricity from renewable sources.

In Fig. 3.12, the spot price on Nordpool's day-ahead market is presented for 2008 and for the day simulated in the case study. As can be seen in the figure, the price varies both by year and by day. This means that the charge profile for the *price-optimal control strategy* would vary accordingly, on a daily basis. Similarly, the cost of charging the PEVs would vary on a daily basis for all control strategies, if customers are to pay hourly electricity price.

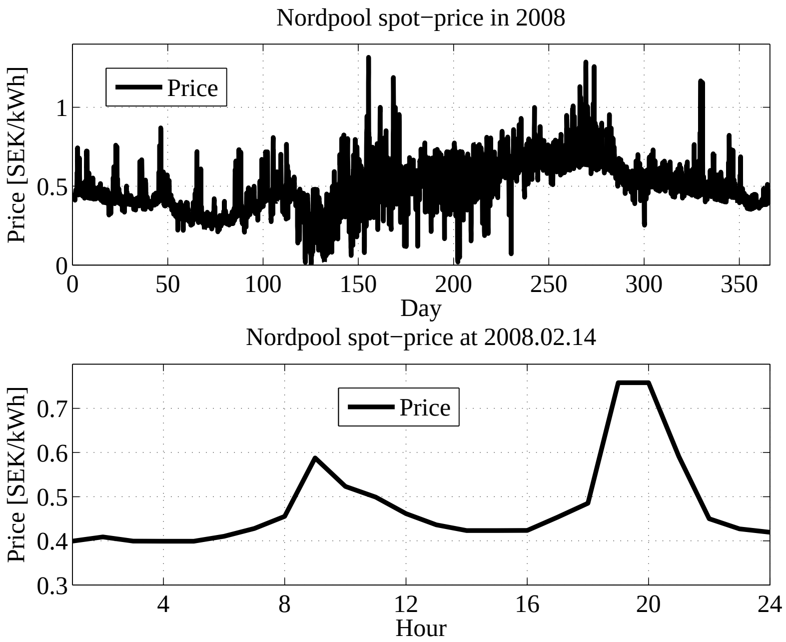

Figure 3.12: Spot-price at Nordpool in 2008, and 14/2 2008 [51].

Chapter 4

Results from the Case Study

4.1 Capacity in the Distribution System

This section presents the calculated capacity of the DS in the two areas studied and is compared to the load profiles presented in Figs. 3.4 and 3.6.

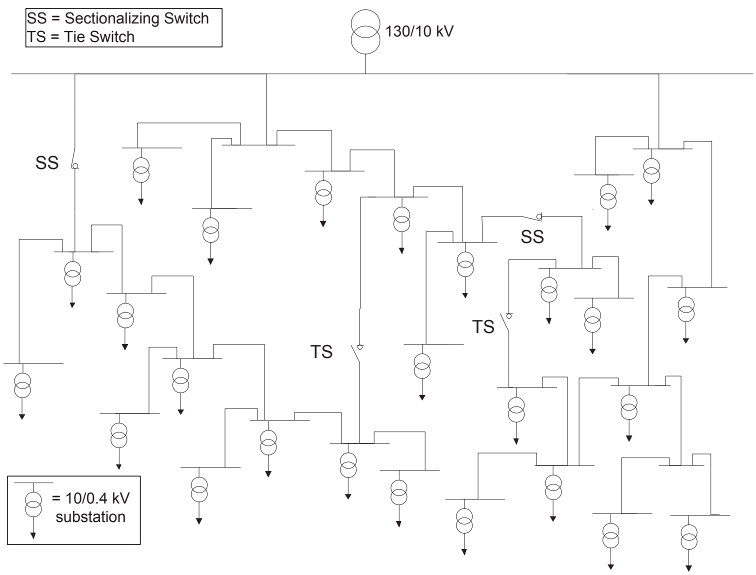

Figure 4.1: One-line diagram of the residential 10 kV distribution system.

As stated earlier, the 10 kV DS of Gothenburg is designed as an OLR-DS. By using the proposed approach shown in Fig. 3.2, the optimal reconfiguration option regarding the capacity was found for the worst case failure, i.e. a failure at one of the main feeders. The sectionalizing switches (SS) shown in Fig. 4.1 and Fig. 4.2 indicate the optimal reconfiguration for the DS's in case of a disconnected feeder.

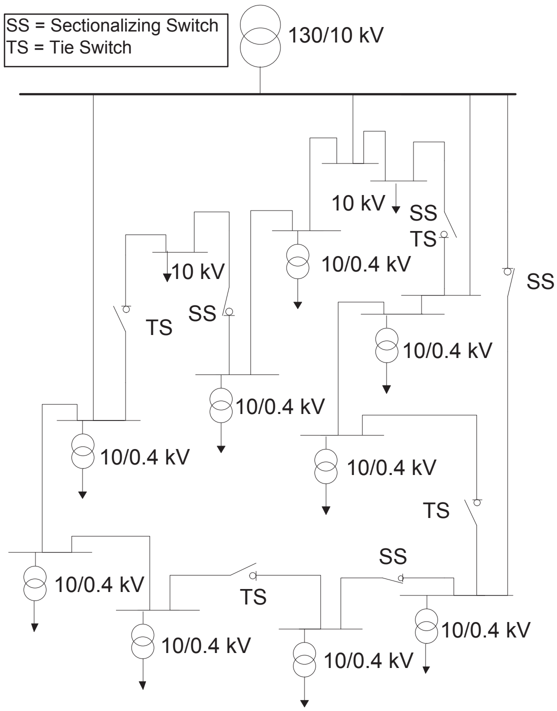

Figure 4.2: One-line diagram of the commercial 10 kV distribution system.

As stated in Chapter 3, the capacity depend on the thermal limits of the cables and transformers, but also on the voltage drop in the system and how the loads are distributed between the substations. Table 4.1 presents the maximum capacity of the DS's for the situation when the load increases linearly between the substations, both for normal operation and for operation in redundancy mode, i.e. with one feeder disconnected.

Fig. 4.3 presents the load profile together with the maximal capacity. As can be seen, the capacity considering the redundancy

Table 4.1: Maximum capacity and peak load.

	Residential	Commercial
Peak demand [MW]	7.91	7.76
Max capacity normal mode [MW]	10.04	13.66
Max capacity redundancy mode [MW]	7.63	9.68

is violated in the residential area during peak hours. This indicates that no PEVs can be charged in this area with maintained redundancy. For the commercial area, it can be seen that the system is operated with a high safety margin.

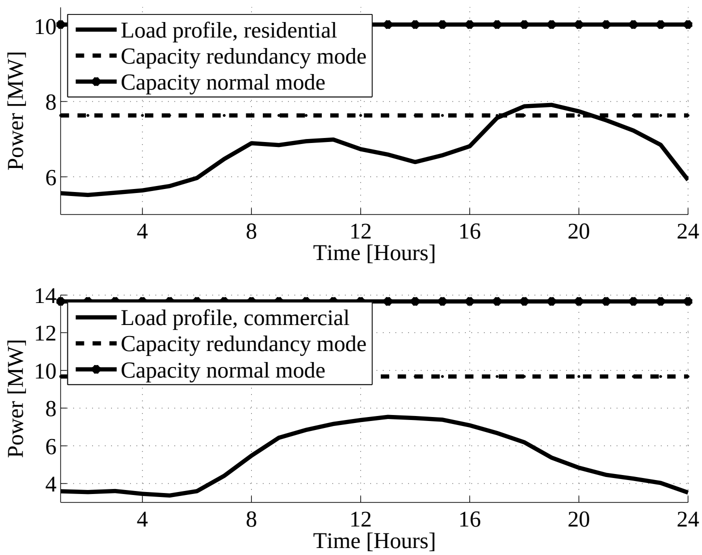

Figure 4.3: Load profiles with maximal capacity for the DS in the residential and commercial areas.

For the residential area, the capacity considering redundancy is limited by one of the cables and the capacity considering normal operation is limited by one of the transformers. If the load could be shifted between the substations, the capacity could be increased since the load at the overloaded transformer could be shifted to another substation. By shifting the load, total system losses could also be decreased, which in addition would increase the usable power transfer. This could be achieved by re-designing the LV-DS, which today is designed as a radial DS, to an OLR-DS, where the LV-DS could be fed by two different transformer stations. This is, however, costly and other techniques, such as load management, would probably gain similar effects but at a lower cost.

4.2 Impact on the Distribution System due to PEVs

This section presents the results from the case study investigating the impact on the DS due to PEVs, for Scenario A, with only home charging, and Scenario B, with charging conducted both at home and at work. Similarly to the capacity, the maximum penetration level varies for the different areas and is presented in Table 4.2. As can be seen, since the capacity is already violated, no PEVs could be charged in the residential area with maintained redundancy. For the commercial area, the maximum penetration level is above 100% for all strategies, i.e. all vehicles could be charged in this area, if they were replaced with PEVs.

Table 4.2: Maximum penetration level.

		Residential		Commercial	
		Normal	Redund.	Normal	Redund.
Uncontrolled	Scen. A	76%	0%	>100%	>100%
charging	Scen. B	>100%	0%	>100%	>100%
Loss-optimal	Scen. A	>100%	0%	>100%	>100%
charging	Scen. B	>100%	0%	>100%	>100%
Price-optimal	Scen. A	49%	0%	>100%	>100%
charging	Scen. B	49%	0%	>100%	>100%

The results below are presented for a full penetration of PEVs, i.e. all vehicles are PEVs. Although this is not possible for the residential area, the result is included to make the comparison. Fig. 4.4 and Fig. 4.5 present the charge profiles for the different control strategies for the residential and commercial area, respectively. As

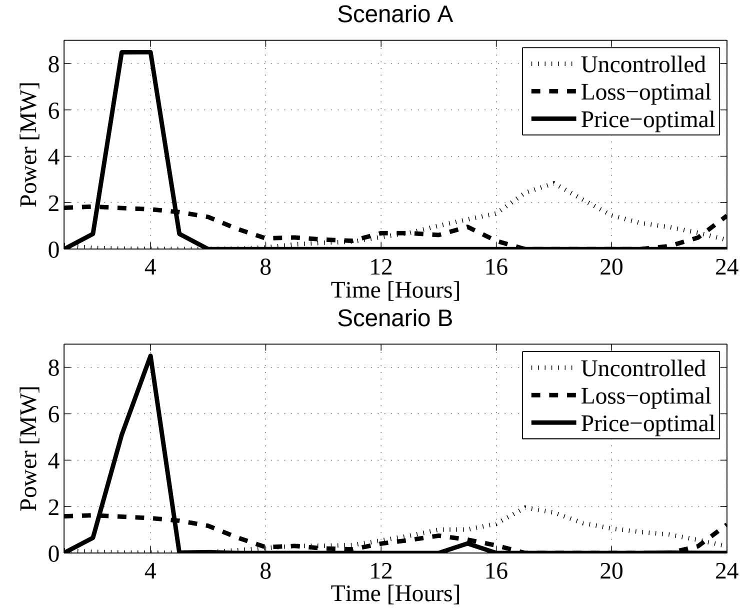

Figure 4.4: Charge profiles for the different control strategies, residential area.

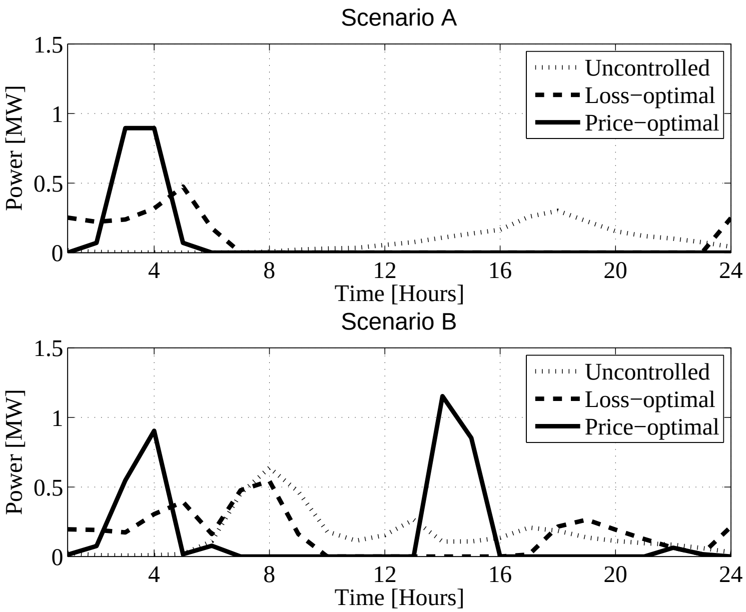

Figure 4.5: Charge profiles for the different control strategies, commercial area.

can be seen, peak power varies both in time and power between the different control strategies. In the residential area, most PEVs will be charged during the afternoon for the uncontrolled strategy, while for the *loss-optimal strategy*, the charging will be spread out during the night to achieve a flatter load profile. For the *price-optimal strategy*, since all PEVs react on the same price signals, most PEVs will charge simultaneously, resulting in a high total charge power. As stated earlier, since the electricity price varies daily, the charge profile will also vary for the *price-optimal control strategy*.

For the uncontrolled strategy, the maximum charge power is found to be higher for Scenario A (with only home charging) than for Scenario B (with charging conducted both at home and at work). This is due to the fact that the increased charge time leads to a greater extent of simultaneous charging for Scenario A, as compared to Scenario B and due to the low number of workplaces in the residential area. The same holds true for the *loss-optimal strategy*, although the difference is smaller. For the *price-optimal strategy*, the maximum charge power is limited by the total number of vehicles and the power is, therefore, equal for both scenarios, although the duration of the peak period is longer for Scenario A.

For the commercial area, the total charge power is less than for the residential area since there are less PEVs to be charged compared to the residential area. Fig. 4.5 presents the charge profiles for a 100% penetration of PEVs under the different control strategies for the 10 kV DS in the commercial area. As can be seen, the maximum charge power is higher for the loss-optimal than for the uncontrolled strategy in Scenario A. For Scenario B the majority of the PEVs charging in this area are charging at work, hence, the maximum charge power occurs in the morning for the uncontrolled strategy. For the *price-optimal strategy*, two peaks are visible, one during the night and one during the day, due to two low price periods, as can be seen in Fig. 3.12. Additionally, the PEVs are able to charge at two different locations, i.e. at work and at home. For the *loss-optimal strategy*, the maximum charge power occurs during the morning hours, although the maximum power is lower than for the uncontrolled strategy.

Fig. 4.6 presents the resulting total load profiles for a full penetration (100%) of PEVs for the residential area. As can be seen, the uncontrolled charging would occur simultaneously with the or-

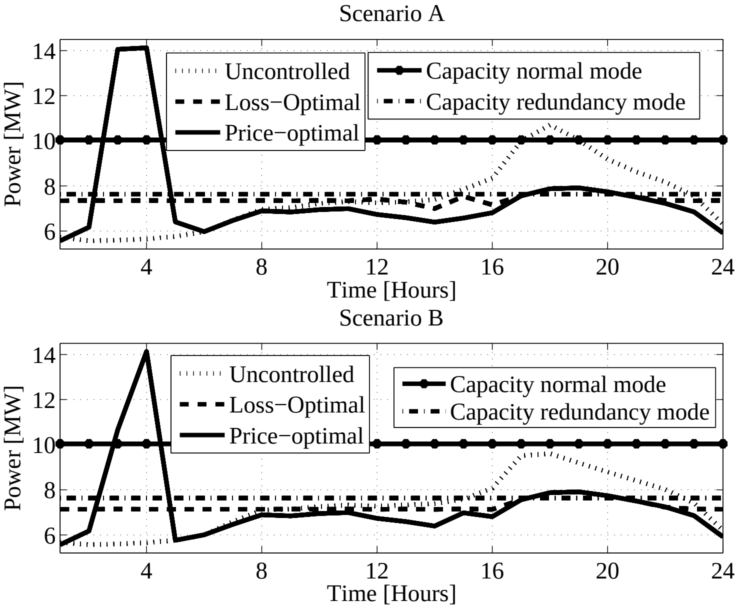

Figure 4.6: Load profiles with a 100% penetration of PEVs, residential area.

dinary peak load. The peak power would increase with between 21 -35% compared to the reference scenario without any PEVs. Although the *price-optimal strategy* would shift the charging to off-peak hours, the increased total charge power would result in a new peak during the early morning hours and the peak power would increase with 78% compared to the reference scenario. The DS would be overloaded for both the uncontrolled and the *price-optimal strategy* for Scenario A, while the DS could handle a full penetration of PEVs in Scenario B if the charging was conducted according to the uncontrolled strategy. With the *loss-optimal strategy*, the DS would be able to cope with a full penetration without increasing the total peak load for both scenarios. However, since the redundancy in the system was violated for the reference scenario, the DS must be reinforced to be operated with maintained redundancy.

Fig. 4.7 presents the total load profile for the commercial area. As can be seen, the charging of PEVs would have a limited impact on the DS. However, the impact would be more severe for the *price-optimal strategy* under Scenario B, when the PEVs could be charged both at home and at work.

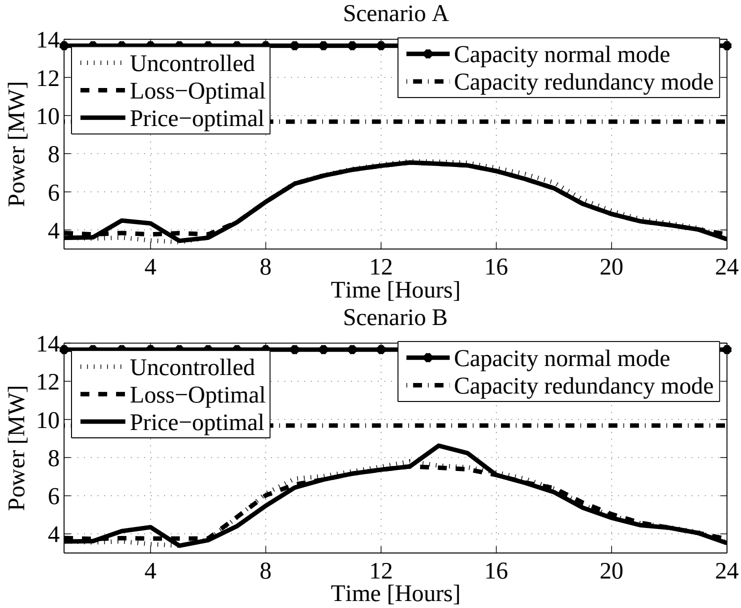

Figure 4.7: Load profiles with a 100% penetration of PEVs, commercial area.

Tables 4.3 - 4.6 present total system losses and minimum voltage for the different scenarios and control strategies under normal operation for the day simulated and with 100% penetration of PEVs. The losses for the reference scenario, without any PEVs, were 2673.2 kWh for the residential area. As can be seen in the Table 4.3 and 4.4, the losses increase by between 460-890 kWh (18-33%). The loss increase is, as expected, lowest for the *loss-optimal strategy* and the losses decrease by more than 100 kWh (about 4%) compared to the uncontrolled strategy. Although the DS would be overloaded, the *price-optimal control strategy* would increase the losses by more than 100 kWh (about 4%) compared to the uncontrolled strategy and is not favorable from a loss point of view. The voltage drop is within the limit for all strategies.

For the commercial area, the losses for the reference scenario were 674.8 kWh. As shown in Table 4.5 and 4.6, the losses increase for all strategies, although the increase is small compared to the residential area. In contrast to the residential area, the losses decrease for the *price-optimal control strategy* compared to the uncontrolled strategy. The voltage drop is small for all scenarios.

Table 4.3: Losses and minimum voltage in the residential 10 kV DS for Scenario A.

	Losses [kWh]	Voltage[pu]
Uncontrolled strategy	3412	0.96
Loss-optimal strategy	3279	0.97
Price-optimal strategy	3560	0.95

Table 4.4: Losses and minimum voltage in the residential 10 kV DS for Scenario B.

	Losses [kWh]	Voltage[pu]
Uncontrolled strategy	3244	0.97
Loss-optimal strategy	3134	0.97
Price-optimal strategy	3345	0.95

Table 4.5: Losses and minimum voltage in the commercial 10 kV DS for Scenario A.

	Losses [kWh]	Voltage[pu]
Uncontrolled strategy	697	0.98
Loss-optimal strategy	688	0.98
Price-optimal strategy	689	0.98

Table 4.6: Losses and minimum voltage in the commercial 10 kV DS for Scenario B.

	Losses [kWh]	Voltage[pu]
Uncontrolled strategy	716	0.98
Loss-optimal strategy	705	0.98
Price-optimal strategy	716	0.98

One of the main reasons for the *price-optimal strategy* are to reduce the electricity cost to the customer. Tables 4.7 and 4.8 present the average cost per charge for customers. For the residential area, the cost of charging according to the *price-optimal* *strategy* is reduced by about 15% compared to the uncontrolled strategy for the simulated day. For the commercial area, the cost is reduced by between 11-16%. Even for the *loss-optimal strategy*, the cost is reduced compared to the uncontrolled strategy (about 11% for the residential and 4-16% for the commercial area).

Table 4.7: Cost/charge [SEK] for 100% PEVs for Scenario A.

	Residential	Commercial
Uncontrolled strategy	7.51	7.51
Loss-optimal strategy	6.61	6.35
Price-optimal strategy	6.29	6.29

Table 4.8: Cost/charge [SEK] for 100% PEVs for Scenario B.

	Residential	Commercial
Uncontrolled strategy	5.67	4.36
Loss-optimal strategy	5.02	4.19
Price-optimal strategy	4.83	3.85

As can be seen in Tables 4.7 and 4.8, the charge cost is higher for Scenario B than for Scenario A. The reason for the increased cost in Scenario A is because that the cost is presented as cost/charge and fewer, but longer, charge occasions are conducted in Scenario A. In terms of money, the savings are between 0.9-1.2 SEK/charge (about US$ 0.15-0.2) for the residential area and between 0.5-1.2 SEK/charge (US$ 0.1-0.2) for the commercial area, if the charging were conducted according to the *price-optimal strategy* compared to the uncontrolled strategy.

As shown in Fig. 3.12, the electricity price varies daily. This will result in different daily charge profiles and savings for customers. The cost presented in Tables 4.7 and 4.8 is the average cost per PEV for this specific day. Similarly, individual savings will vary between the PEVs, depending on when they are charged and to the usage of the PEVs.

4.3 Impact on the Distribution System due to Load Management

This section presents the results from the case study for Scenario C, where no PEVs are available but where some of the existing loads are variable in time, i.e. variable loads. The same control strategies were applied on the variable loads as for PEV loads for Scenario A and B described above. Due to limited information about the loads in the commercial area, Scenario C is only simulated for the residential DS.

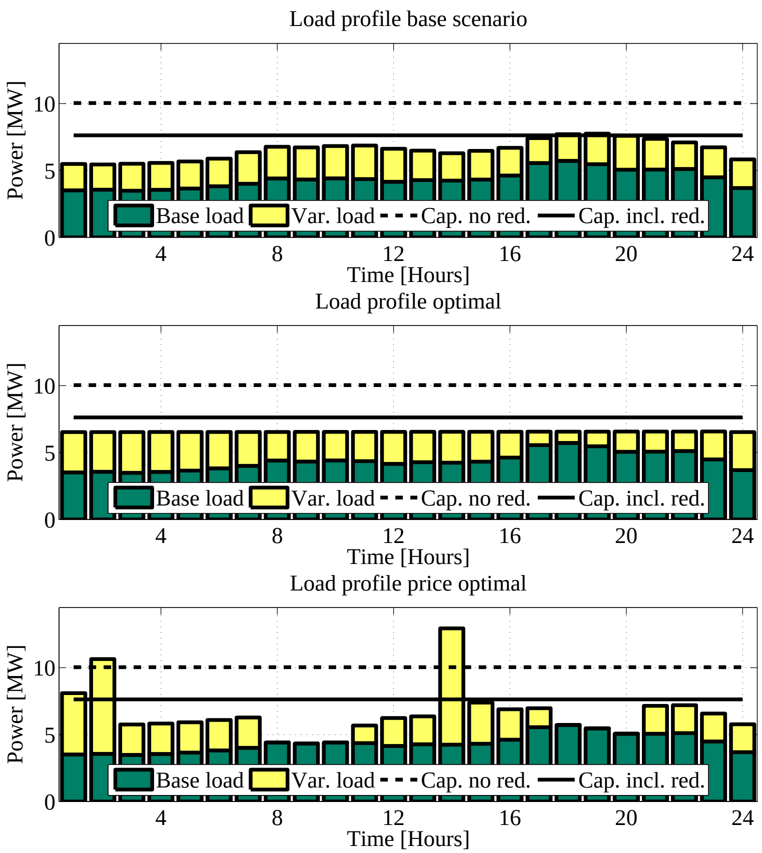

Figure 4.8: Load profiles with variable load for the different control strategies.

By controlling the variable loads according to the *loss-optimal control strategy*, the load variance is reduced considerably. Fig. 4.8

presents the load profiles for the two control strategies. As can be seen, the variable load (”var. load” in Fig. 4.8) is shifted in time and the peak load is decreased for the *loss-optimal strategy* and the capacity of the DS with maintained redundancy (”cap. incl. red.” in Fig. 4.8) is no longer violated. However, for the *price-optimal control strategy*, the peak load is increased compared to the reference scenario and the maximal capacity of the DS (”cap. no red.” in Fig. 4.8) will be violated. As for the case with PEVs, the reason for this is that all customers acquire the same price information and increase their consumption during low price periods.

Fig. 4.9 presents the variable load for the different control strategies. The maximal power that is shifted between the *loss-optimal strategy* and uncontrolled strategy (reference scenario) is 1.19 MW which correspond to 0.6 kW per customer. For the *price-optimal strategy*, the number is 6.6 MW, or 3.4 kW per customer. The maximal heat capacity in each home was assumed to be 4.5 kW. For the *price-optimal strategy*, this is limiting the variable load for hour 14. For the *loss-optimal strategy*, the variable load was maximum 1.6 kW per customer.

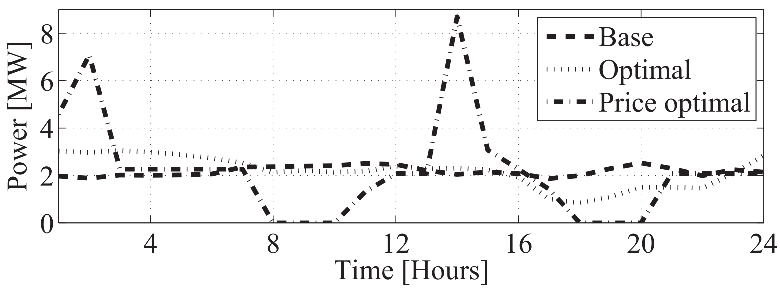

Figure 4.9: Variable power for the different control strategies.

As shown in Fig. 4.8 and Fig. 4.9, the variable power is almost constant for the uncontrolled strategy. Since the model assumes a constant outside temperature, this results in a close to constant temperature inside. Fig. 4.10 presents the temperature variation for the different strategies. Although the temperature is limiting the variable load for both the *loss-optimal and price-optimal strategies*, the temperature stays within the limits. As can be seen in Fig 4.8, the heating system can be turned off for 3 hours without violating the temperature constrains.

Table 4.9 presents the minimum voltage, total losses and electricity cost for the different strategies. As can be seen, the voltage

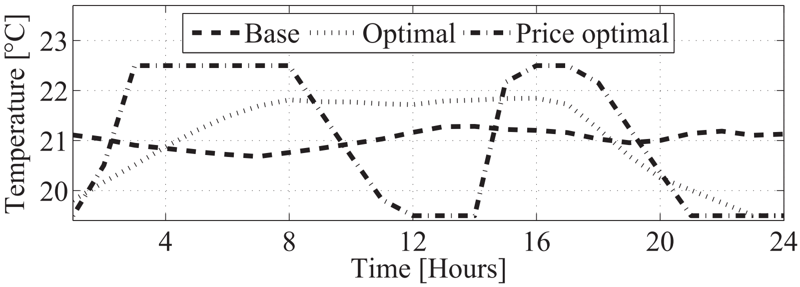

Figure 4.10: Variations in the temperature in the homes.

variation will decrease for the *loss-optimal strategy* and increase for the *price-optimal strategy* compared to the uncontrolled strategy. However, for all strategies the voltage will remain within the limitations.

Table 4.9: Minimum voltage, total losses and electricity cost per customer and day.

	Voltage [pu]	Losses [kWh]	Cost [SEK/cust.]
Uncontrolled	0.97	2673	82.7
Loss-optimal	0.98	2638	82.0
Price-optimal	0.95	2951	81.0

As can be seen in Table 4.9, the total loss for the simulated day decreases for the *loss-optimal strategy* by about 1.3%, but increases for the *price-optimal strategy* by about 10.4%, compared to the uncontrolled strategy.

The cost for the customer decreases by about 1.7 SEK/customer for the simulated day for the *price-optimal strategy* compared to the reference case (uncontrolled strategy). In relation to the total electricity cost, the savings will be about 2%.

4.4 Impact on the Distribution System due to PEVs and Load Management

This section presents the result from the case study for Scenario D and E, i.e. applying the control strategies both on PEVs and on the variable loads in the homes. As for Scenario C, these scenarios are only performed for the residential area.

Fig. 4.11 presents the load profile for the different control strategies under Scenario D. As can be seen, the load increases above the limit for the *uncontrolled and price-optimal strategies.* As for Scenario A, the maximum penetration of PEVs is 76% for the *uncontrolled strategy*, without considering the redundancy criteria. For the *price-optimal strategy*, no PEVs can be supported since the capacity in the DS is violated by the variable load, as shown in Fig. 4.8. For the *loss-optimal control strategy*, a full penetration of PEVs can be supported, without violating the redundancy of the system.

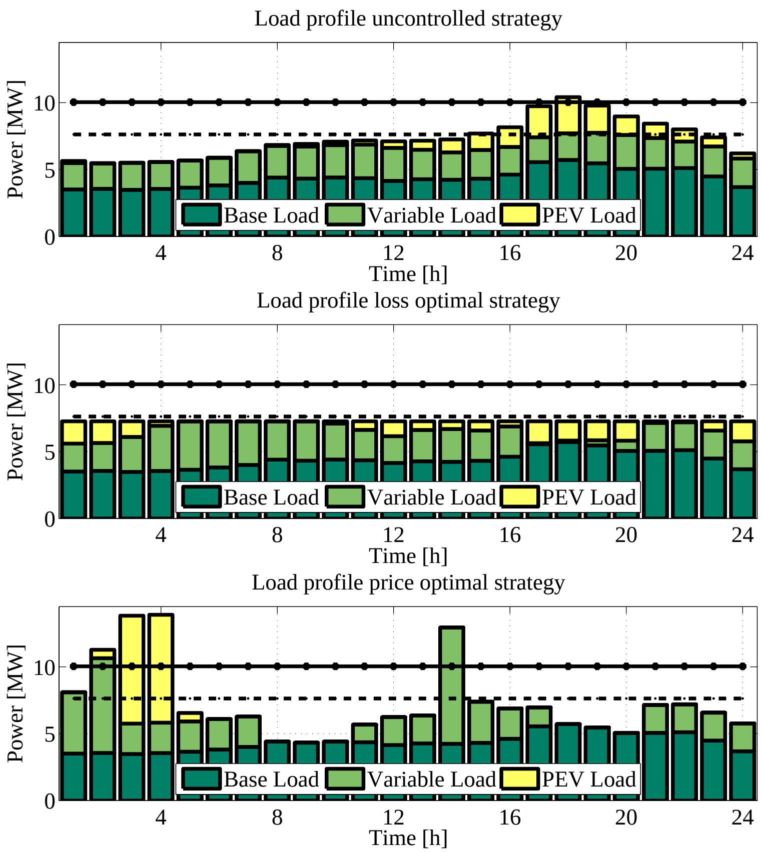

Figure 4.11: Load profiles with PEVs for Scenario D.

Fig. 4.12, presents the load profile for the different control strategies under Scenario E. As can be seen, the uncontrolled strategy can handle a full penetration of PEVs while the load increases above the limit for the *price-optimal strategy*. As for Scenario D, the *loss-optimal strategy* can handle a full penetration of PEVs, without violating the redundancy in the system.

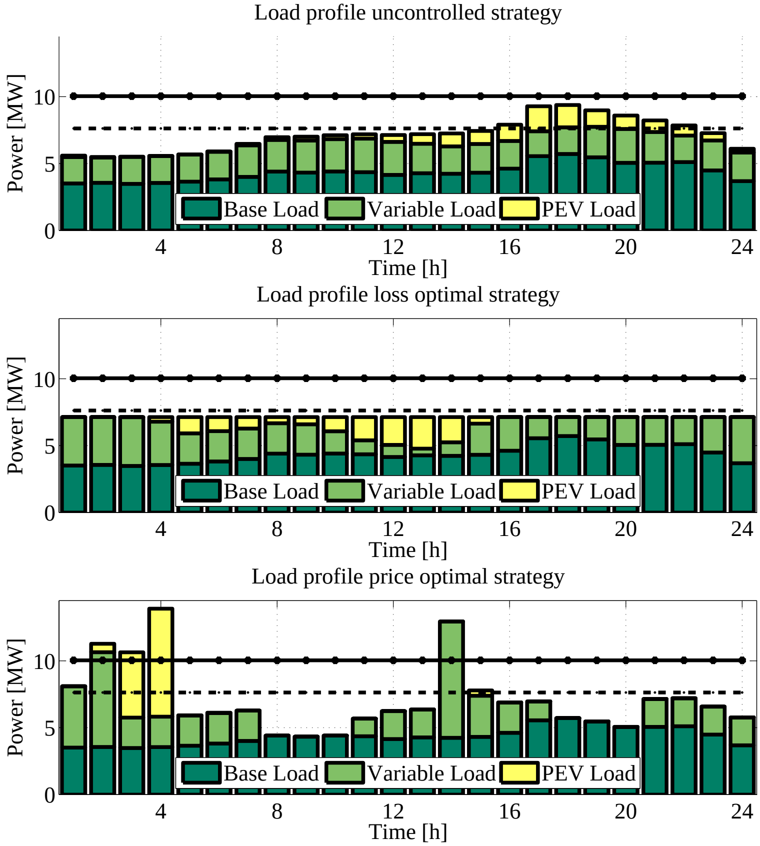

Figure 4.12: Load profiles with PEVs for Scenario E.

As can be seen in Fig. 4.11 and Fig. 4.12, the power of the variable load varies between Scenarios D and E for the *loss-optimal strategy* because both the variable loads and the PEV loads are controllable in time and can vary mutually while still obtaining the same cumulative load profile. As shown in Fig. 4.10, the temperature variation increases with the proposed control strategies for Scenario C. The same holds for Scenarios D and E and are in fact larger for these scenarios. Fig. 4.13 presents the temperature variations for Scenarios D and E. However, the variable load can be shifted differently given the presence of PEV loads with the same cumulative load profile. Simulations with a reduced temperature range between $21 \pm 0.5°C$ provides the same cumulative load profile but with lesser temperature variations.

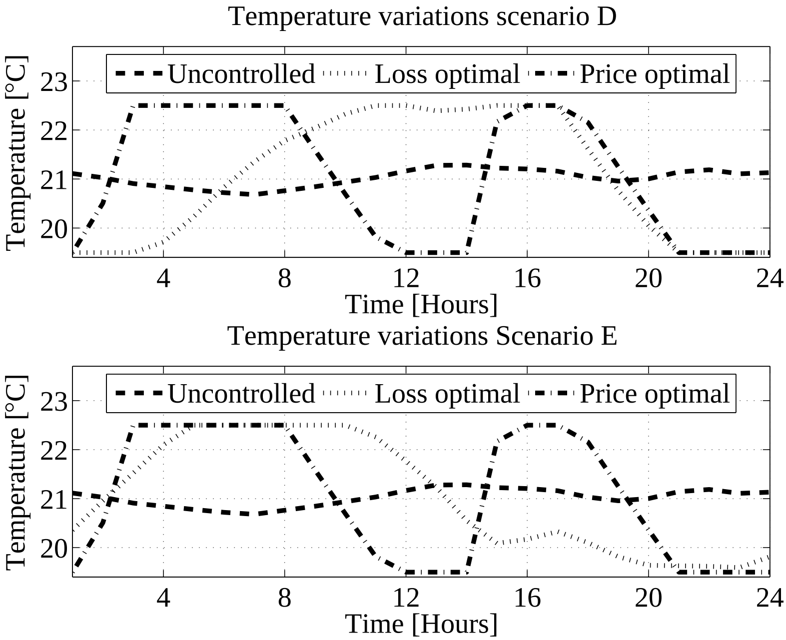

Figure 4.13: Variations in the temperature in the homes.

Tables 4.10 and 4.11 present the minimum voltage, total losses and average electricity cost per customer, for the different strategies and Scenarios. As can be seen, the voltage variation will decrease for the *loss-optimal strategy* and increase for the *price-optimal strategy* compared to the uncontrolled strategy. However, for all strategies, the voltage will remain within the limitations. The losses are decreased by between 3-4% for the *loss-optimal strategy* compared to the uncontrolled strategy, while it increases with 13-14% for the *price-optimal strategy*. The cost is decreasing for both the *loss-optimal* and *price-optimal strategies* compared to the uncontrolled strategy. The cost reduction is about 1% for the loss-optimal and about 3% for the *price-optimal strategy*.

Table 4.10: Minimum voltage, total losses and average electricity cost per customer and day for Scenario D.

	Voltage [pu]	Losses [kWh]	Cost [SEK/cust.]
Uncontrolled strategy	0.96	3412	92.38
Loss-optimal strategy	0.98	3277	91.06
Price-optimal strategy	0.94	3892	89.12

Table 4.11: Minimum voltage, total losses and average electricity cost per customer and day for Scenario E.

	Voltage [pu]	Losses [kWh]	Cost [SEK/cust.]
Uncontrolled strategy	0.97	3243	90.41
Loss-optimal strategy	0.98	3149	89.32
Price-optimal strategy	0.95	3670	87.58

Chapter 5

Conclusions

This thesis presents an approach to assess the impact of plug-in electric vehicle (PEV) charging strategies on an open-loop-radial distribution system (OLR-DS). The approach uses demographical data and travel surveys to determine when and where the PEVs can be charged. Three different control strategies are investigated and applied to the PEVs charging. In addition, the control strategies are applied to the existing non-time-critical loads in the electrical distribution system (DS), including space and tap-water heating.

A case study on two sections of the DS of Gothenburg, Sweden, is performed. The case study shows a large difference in the timing of when the charging is performed for the two areas, indicating the importance of considering the type of area where the DS is located, e.g. by using demographical data. Further, the peak power in the residential DS will increase by between 21-35% if the charging is uncontrolled. In the commercial DS, the peak demand will increase by between 1-3%. If the customers are exposed to hourly electricity prices and seek to minimize their electricity costs (i.e. in *price-optimal strategy*), the peak power will increase by 78% for the residential area and by 14% for the commercial area. On the other hand, if the charging is controlled according to the *loss-optimal control strategy*, the charging would be conducted during off-peak hours without increasing the peak demand. However, the reduction in losses was rather limited, even for a full penetration of PEVs (by about 4% of the total losses in the system). The main advantage of this strategy is that it would reduce the need for reinforcement of the DS.

By applying the *loss-optimal control strategy* on non-time-critical loads, i.e. space and tap-water heating, the peak power would be reduced by almost 10% without affecting the customers comfort. The *price-optimal control strategy* would on the other hand increase the peak demand by more than 80% compared to the reference scenario. However, the results indicate that the average saving from controlling charging and loads according to the *price-optimal strategy* will be limited in the Nordic countries (about 3% of the total electricity cost) and additional measures may be needed to give customers enough incentives to change their electricity usage habits.

Chapter 6

Future Work

With recent technology developments in the electrical power system (PS), several possibilities would be possible, such as integration of renewable generation and improved operation of the distribution system. This study showed that there exists a large potential for load management in the PS, both for existing loads and PEV loads using different control strategies. However, it was also shown that using the spot price as the only control parameter would increase the stress on the distribution system rather than decreasing it. As a continuation of this work, other more suitable control strategies, based on customer incentives, will be proposed and investigated. Additionally, it is proposed to investigate other alternatives to manage peak power, e.g. local energy storage or vehicle-to-grid (V2G).

The roll-out of smart meters could provide more detailed load data, enabling opportunities to perform more accurate studies. This would be especially valuable when studying the impact of different control strategies on a low voltage distribution system (LV-DS). In Gothenburg, smart meters have been in operation since 2009 and an extensive study of the LV-DS in Gothenburg can be performed.

The heat model used in this thesis has been simplified to a large extent. For the continuation of this project, it is proposed to improve the model to include more details. Similar to load data, this is also important when studying the LV-DS.

A large share of total electricity consumption in Sweden is used for heating purpose. During the last years, the number of installed heat pumps has increased considerably. The characteristics of a heat pump differs from other heating system and may offer new possibilities for the DS. An investigation of if/how the heat pump could be used and managed to improve the DS is suggested.

With increasing electricity cost, the interest in small scale electricity production units, such as micro-CHP and photo-voltaic, are increasing. For the continuation of this work, it is proposed to investigate how these systems will impact the LV-DS.

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